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Vol. 220 NOVEMBER, 1935 No. 5

GLASS: AN INDISPENSABLE FACTOR IN MODERN CIVILIZATION.[1]

BY

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Somewhere, more than five thousand years ago, a method was discovered for making glass. Perhaps a number of methods came into being independently. Ancient civilizations in Egypt and other lands possessed glass articles which the archæologist has brought to light. Some of these are at least five thousand years old. One method attributed to accident was described by Pliny, who claimed that Phœnician sailors landing on the shores of the Belus River wished to prepare their noonday meal. It was customary to cook the food in kettles supported by stones. Failing to find kettle stones on the sandy shores of the river, they took lumps of natron to support the vessels. The heat of the fire melted the natron, which reacted with the wood ashes and the sand of the shore to form glass.

Though hollow objects, such as flasks, were made in Egypt at least 1500 B.C., the minerals from which the glass was prepared were probably dropped on to clay cores and, melting

[1] Presented at a meeting held Thursday, February 7, 1935. Contribution No. 300 from the Department of Chemistry, University of Pittsburgh.

(Note—The Franklin Institute is not responsible for the statements and opinions advanced by contributors to the JOURNAL.)

to a layer of sufficient thickness, cooled slowly over the fires. When cold, the clay was washed from the interior of the flask. The blow pipe was not invented until about the beginning of the Christian era. The inventor of this important device on which molten glass could be gathered and blown is unknown.

Although the topic of this lecture deals with the indispensability of glass to modern civilization, it might be well to devote a little time to the consideration of its value to the older civilizations. Glass was highly prized for its delicate beauty and was considered a prize of war. Consequently, the art traveled with the victorious armies, from Egypt to Greece and into Rome, Rome even demanding tribute in glass rather than gold. The value depended not alone on beauty, but on the very fragile nature of glass, and it is said that during the time of Tiberius an artificer who had invented malleable glass [3] was called before the Emperor. Upon displaying a bowl which had been shaped from the material, he threw it to the ground and after it became indented hammered it back into its original shape. Tiberius inquired "Knoweth any man thy secret?" and upon receiving a reply in the negative ordered him beheaded.

With the fall of Rome, the secrets of glassmaking traveled eastward into the Byzantine Empire and later with the fall of Constantinople, into the northern Italian cities. Venice prized the art so highly that a Council of Ten was created to guard the secrets. It was a law that anyone who carried off these secrets was to suffer the death penalty. In the event that he escaped, his relatives were imprisoned and their worldly effects confiscated. Despite these precautions, Venetian deserters carried the art to the countries of western Europe.

Next comes the discovery and colonization of America. Already in 1607 a glass factory was established about a mile from Jamestown in the colony of Virginia. According to Captain John Smith in his History of Virginia, this was the first industrial enterprise in the American colonies. The

[3] A mineral known as horn silver occurs in Italy. It is silver chloride and when melted forms a glassy substance which is malleable. It was probably this and not glass to which the historian referred.

factory produced bottles and beads, the latter for trade with the Indians. A movement is underway at present to restore the site of the old Jamestown factory and build a museum which shall house specimens from this and subsequent enterprises, together with the later developments so that the display will indicate the evolution of glass manufacture in America. An interesting story might be told about this American evolution, but we shall confine ourselves to glass and its influence on modern civilization.

As nearly everyone knows, glass is made by heating sand, limestone and soda ash together at white heat. This simple combination of substances may be employed in many ways and the product fabricated into plate glass, window glass, bottles, optical glass, and other types which will be considered in turn. Your speaker is often inclined to quote Dr. Samuel Johnson, who, in an article which he published in England during the latter part of the eighteenth century, said:

"Who, when he saw the first sand or ashes by a casual intenseness of heat melted into metallic form, rugged with excrescences and crowded with impurities, would have imagined that in this shapeless lump lay concealed so many conveniences of life as would in time constitute a great part of the happiness of the world? Thus was the first artificer in glass occupied, though without his own knowledge or expectation. He was facilitating and prolonging the enjoyment of light, enlarging the avenues of science, and conferring the highest and most lasting pleasures; he was enabling the student to contemplate nature and beauty to behold herself."

Dr. Johnson anticipated the significance of glass to modern civilization.

Of the types of glass already indicated, I shall first consider *plate glass*. This was invented in France in 1688 by Lucas de Nehou. Glass was melted in open pots or crucibles and poured on to steel tables fitted with tracks near either edge. A large steel roller was drawn over the molten glass and the plate that formed was then slowly cooled or annealed to remove strains which would have resulted from rapid cooling. The annealing furnaces are called lehrs. On removal from the lehrs, the plates were imbedded in plaster on large circular tables and the surface ground level by sand or

other abrasives and water through iron-studded discs which rotated over the surface. The abrasive was then washed off and the surface polished through felt pads fed with rouge and water. The plates were naturally reversed and ground and polished on the other side. This process of the latter seventeenth century is still in use and though the mechanical details have been improved, the principle remains unchanged. In other words, plate glass can be made like the pie crust, by running the rolling pin over the dough. In the latest inventions, the glass is melted in huge tanks, flows from the tanks between rolls, forming a continuous plate which is afterwards cut, ground and polished.

Window glass was originally cast and that which is found in the old Roman baths was of this type. In the twelfth century, an Anglo Saxon monk, Theophilus, conceived the idea of gathering glass on a blow pipe, blowing a bubble, cooling it until it set partially, again dipping it into the pot and so blowing, cooling and dipping repeatedly until he had a sufficient mass of glass to form a huge bubble. This was elongated and lowered between parallel charred wood walls so that it formed a cylinder during blowing. The cylinder was annealed and then cracked off at the top and bottom by means of a thread of hot glass after the cylinder had been scratched. It was later split lengthwise by making a scratch on the interior and running an iron bar, red hot at one end, back and forth until the cylinder cracked. The cracked cylinder was introduced into a flattening oven where it was heated up slowly until the glass began to soften and open up. A flat charred wood paddle assisted in the operation. The first cylinders were probably not over eight inches to a foot in diameter and five or six feet long. This invention of the twelfth century was in vogue, in principle at least, until the latter part of the nineteenth century and though the glass was melted in tanks instead of open pots, and mechanical developments naturally accompanied the procedure, it was largely a hand method except for the use of compressed air instead of lung power.

About 1890, Lubbers converted the hand process to a mechanical one. He designed a pipe over forty feet long, with a larger gathering end or bait. This was suspended and

controlled mechanically. The glass was melted in large tanks and ladled from the tanks into shallow pots or crucibles. The bait was brought into contact with the glass and as soon as this adhered, compressed air was introduced while the bait rose slowly, thus forming a bubble on the surface of the glass. When the bubble acquired a diameter of some thirty inches, the air pressure was reduced until it was slightly greater than atmospheric pressure, or just enough to prevent collapse of the bubble. Thereafter the pipe was raised slowly and according to its rate of travel the cylinder was thick or thin. The Lubbers cylinders, thirty inches in diameter and over forty feet long, were then lowered on to supports, the bait was cracked off, a diamond scratch was made about every six feet, wires passed around at the diamond scratches and heated electrically to crack the whole into short cylinders and these in turn were scratched and cracked into halves, flattened and annealed. The invention of Theophilus, through the genius of Lubbers, became a mechanical window glass process.

Inventors who wished to improve upon the cylinder process naturally turned their minds to a continuous sheet. The early stages of this development were at times humorous in the number and variety of impractical patents granted to protect such ideas. Eventually, about the beginning of the present century, Fourcault in Belgium invented a continuous process in which a bar of iron was lowered into a tank of glass, then raised slowly and, as the sheet formed in cooling, it was drawn up between rolls. The rising current of heat from the sheet of glass served to anneal it. Though development required many years, the process was successful, but it had one disadvantage, namely, the cracking off of the continuous sheet into smaller sheets for trimming and storage. If an accident occurred, the broken glass fell down into parts of the apparatus where the rest of the sheet was forming. However, there have been such improvements, that the Fourcault process is in use in many plants throughout the world. Colburn of Franklin, Pennsylvania, surmounted the obstacle of having the sheet travel vertically, by having flames play upon it at a certain point and drawing it over a huge roll in a horizontal direction. The glass was then annealed in properly constructed shallow ovens and could be

handled while lying on the supporting conveyors. This process is also used extensively throughout the world and the two have so replaced the old cylinder process that there is hardly a single one of the latter plants to be found in America today. The manufacture of window glass in continuous sheets has brought science into the picture, not only in its applied engineering but through physical control of temperature and through the chemical control of the glass composition. Taking window glass as a whole, enough is manufactured per annum to pave a boulevard around Mother Earth at the Equator eight lanes wide.

Mirrors are usually manufactured from plate glass. The cheaper ones are made from window glass. Early Venetian mirrors were made by placing a pane of glass in a frame, running mercury over the surface and then applying a sheet of tin foil under pressure. In 1885, a French chemist, Petitjean invented a process for depositing silver from an aqueous solution of the nitrate through the addition of ammonia and organic reducing agents. This, with the invention of plate glass in France, practically destroyed the Venetian mirror industry. The first of the Petitjean mirrors were used in the Galleries des Glaces at Versailles, in which the Peace Treaty was signed after the World War. Further scientific developments of the Petitjean process have enabled us to manufacture mirrors at a cost of one cent per square foot for the silver utilized. Fortunately, the old Venetian mirrors were usually housed in beautifully carved frames, some of them by eminent artists of the time, and so they have become precious objects of ancient art.

A word about three new developments in mirror making. The first of these involves the deposition of silver from a solution on the same principle as the Petitjean method, except that improved reagents are employed for the reduction. It is now possible to deposit the silver film so thin that a mirror is perfect when one looks into it to see his reflection, but transparent if one looks from the dark side through into a lighter space. Such mirrors enable an observer to see what is going on on the other side of a partition without being observed himself. They are utilized in a variety of ways, one of which is the observation of nervous patients or abnormal

individuals in hospitals who fret at the presence of another person in the room. The transparent mirror may also be utilized for observing criminals.

The second process involves the spraying of metal, which is heated in an arc, onto the cold surface of glass. Aluminum-coated and other reflectors of this type are used in display windows for throwing light upon exhibits. The third process involves the use of a vacuum unit. Aluminum or an alloy of aluminum and magnesium is placed on a tungsten trough which is heated through its resistance to the passage of an electric current. The glass plate or reflecting lens which is to be coated is suspended above the trough in the vacuum and when the current is turned on, the metal vapor condenses on the outer surface of the glass. All other reflectors are coated on the under surface and one must look through the glass before getting the reflection. The new mirrors not only possess the advantage that they are on the near surface, but they reflect light uniformly in all colors of the visible spectrum and even in the ultra violet. These mirrors are especially valuable in astronomy for recording the color and therefore the composition of the stars, and giving us details which would not otherwise be visible.

Long after the utilization of *plate glass* for mirrors and windows, the idea of *reinforcing* it to prevent accidents was conceived. At first a wire with one-inch meshes was imbedded between two layers of glass which were passed through suitably constructed rolls. Afterwards, wire glass which contained single strands instead of meshes was on the market. After some years, the notion of cementing two or more layers of glass together with an organic plastic bond had its birth. In this scheme, a variety of plastic materials of a celluloid-like, thin, nonflammable nature is applied as sheets laid between two or more plates of glass which are then firmly pressed together in such a way as to prevent the inclusion of air bubbles. The plates are cut to size and the edges are so treated as to prevent further action of air on the bond between the plates. This is the laminated, or safety glass, which is now employed in automobiles and which, in greater thicknesses, serves in bank windows and armored cars for protection against hold-ups. It is virtually a bullet-proof ma-

terial. In a specimen which the speaker has frequently exhibited, there are three layers of glass, an outer one one-eighth of an inch thick, a middle, three-fourths of an inch thick, and a third one also one-eighth of an inch thick. This one inch disc has been fired at at a distance of only ten feet by a machine gun discharging steel-nosed rifle bullets. The first thin layer has been chipped away where the bullets struck. The middle layer is cracked radially, and the third layer, one-eighth of an inch thick, is still intact, though the specimen is over fifteen years old and has been transported many times in connection with lecture demonstrations. Laminated glass possesses a safety value for automobile use which lies in the fact that when it breaks, instead of flying in large sharp pieces which might produce serious injuries, it merely shatters and the particles are held by the plastic bond. In a very recent development, the bond itself is flexible so that in case of accident, if one happens to strike the windshield, the glass not only cracks and adheres to the plastic, but the plastic layer gives and lessens the shock. The very latest development eliminates the use of reinforcing materials. In this the plates are heated after grinding and polishing and are then subjected to a uniformly applied and well controlled stream of cold air which chills the surface, producing a case-hardening effect. Prior to the use of air, similar plates were produced by dipping into cold oil and chilling the surface uniformly. If these plates break, they shatter into thousands of tiny fragments instead of forming the larger pieces which might produce more serious accidents. Heat-tempered plate glass has another interesting property. It bends to an appreciable extent without breakage and has even been employed for diving boards in some swimming pools. Of course, all case-hardened glass will shatter if the surface is scratched for it is made on the principle of the old Prince Rupert drop, which shattered explosively when scratched.

We cannot leave *plate glass* without saying a word about its use as a *structural material.* It is now made in black and various colors and at times consists of a colored layer with a very thin upper layer of a second color. Designs can be etched through or sandblasted by means of stencils and this glass is used for corridor walls or for store fronts, etc. The

effects are beautiful. Recently, an entire building was constructed of glass and steel in England. The use of safety glass for structural purposes has already gained considerable headway in America.

Let us now turn our attention to *bottles*. Originally, or at least since the beginning of the Christian era, all hollow objects were blown from a gather of glass on a pipe about the size of a billiard cue, the wide end of which was introduced into the vessel containing the molten glass. Bottles were also made in this way. Then came air compressors and instead of using lung power entirely, the gather for larger bottles was made by hand, partially blown by mouth and then fully inflated by attaching a hose from a compressed air line. In 1899, Michael J. Owens started a series of experiments to produce a finished bottle by mechanical means. It must be borne in mind that prior to this time, after the bottle had been shaped on the pipe from the original bubble, it was necessary to crack the object from the pipe, heat the cracked portion and shape the neck. Owens hoped to produce a finished neck without a separate step. He started with a ladle of glass from which he sucked glass into a mold shaped like the upper half of a bottle by drawing the piston of an air pump which was attached to the top of the mold; this half was then placed over the lower half of the mold and the plunger was forced back again. The portion to be the neck of the bottle had already cooled and set with the consequence that the rest of the glass, the softer portion, was forced into the lower half of the mold and the bottle was complete with a finished neck. Later, the single implement evolved into a machine which in some instances had as many as twenty-four gathering and blowing arms which traveled continuously over the molten glass, sucking it up successively. In one of the modern machines, there are six openings in a single mold, so that six bottles can be blown by a single unit. In a plant which your speaker visited within the last two years, ten Owens machines of the single mold type were in use, five of them equipped with ten blowing arms each and the other five with fifteen, and these ten machines produced over a million beer bottles every day. The machines have been so modified as to molds and operation that they are no longer limited to bottles, but can be utilized also for the manufacture of tumblers, etc.

In connection with the manufacture of hollow ware, we now consider *electric light bulbs*. These also were originally blown by hand. A machine by Westlake was the first important mechanical development. In this all of the manipulative steps of the hand workmen were reproduced mechanically. The Westlake machines were employed all over the world, but a newer development has come through a recent patent covering the conversion of a ribbon of glass into the bulbs. The glass flows from the tank through a spout between a pair of narrow rolls, one of which is indented with concave depressions. The ribbon therefore has a series of lenses in relief. Each of these, passing over a conveyor which has an opening under the lens, is brought into contact with a blowhead which forces the lens portion through the opening, thus blowing a bulb. The bulb in turn enters a mold and as there is no blowpipe which can rotate the mold itself does. After blowing, the bulbs emerge from the molds, are cut off mechanically above the conveyor, drop onto a belt which carries them to the annealing ovens and are cooled slowly to room temperature. Two machines in operation in Cleveland, Ohio, are turning out over a million lamp bulbs per day and the total American production now exceeds two million bulbs per day.

While a variety of hollow ware is manufactured by machine, those articles for which there is not a sufficiently large demand are still made by hand. Frankly, there is nothing more fascinating than watching a real artisan take his bubble and shape it while on a bench with parallel arms, applying charred wood paddles, iron implements, etc.

Pressed ware is being manufactured at an ever-increasing rate. Here, like in the Owens bottle machine, there is the advantage that a finished article results. To press an object, one uses a mold, which may consist merely of a bottom and top, as in the pressing of lenses for traffic signals, or a bottom of two, three, or even more pieces which are hinged together. For the manufacture of reflector globes, glass tableware, or large lighting bowls, a plunger enters the mold and distributes the soft glass between the mold and plunger. The glass may be introduced into the mold by gathering on an iron rod or pontil for small ware, or by actually ladling it into the mold

for larger ware. In some cases the glass flows continuously through spouts and is sheared off according to the size of the mold employed. This principle is in use in the manufacture of cheap lenses, marbles, etc. Most of the inexpensive tableware which is on the market today consists of pressed pieces.

All articles to which previous reference has been made consisted of common lime glass made as already indicated. In 1620, England gave the world lead-potash glass, then called *flint glass* because a pure variety of flint was employed instead of sand, while the lime product had been known as crown glass. With the introduction of lead and potash, a higher index of refraction resulted, with a brilliant play of light. The unpleasant, high-pitched ring of lime glass gave way to a rich, low resonance in the lead glass. This combination of properties which pleased the eye and the ear made flint glass popular for the finer drinking glasses, punch bowls, etc. The potashes, so-called because they resulted from the wood which was used as fuel in the furnaces, were limited. A supplementary supply, while quite small, could be obtained through extracting sheep's wool and after removing the lanolin, or grease, igniting the residue. A search for new sources of potash followed and it was later produced in large quantities from sugar beet waste after the extraction of sugar; also from such natural deposits as those in Stassfurt and Alsace Lorraine, and still later in America, where we now have an independent source of supply.

While considering flint glass, it might be appropriate to take *optical glass* into account for most optical systems utilize both crown and flint glass, the one compensating against the production of color fringes coming through lenses of the other type. A suitable combination of crown and flint can practically eliminate color fringes. In addition to the lime and lead glasses, whose index of refraction is quite different, the latter property can be altered almost at will by suitable variation of chemicals employed in the batch or mixture of raw materials for producing the glass. Prior to 1880, only five chemical elements or their compounds were employed in optical glassmaking. Then Ernst Abbé published an article in Germany in which he bemoaned the fact that very little research had been done in the optical glass field. It came to

the attention of a young chemist, Otto Schott, who immediately communicated with Abbé and asked to become associated with him. Abbé welcomed him and with the wise subsidy created by the German government a series of investigations were undertaken. In the twenty-five years which followed, as many new chemical elements or their compounds were added to the list for optical glass. Important among these were barium and boron. Today, there is an optical glass to care for practically every correction of human vision that is necessary and to meet the needs of various scientific instruments. Otto Schott is over eighty years old, still living in Jena, Germany, where he visits the factory and laboratory from day to day. The sixtieth anniversary of his receipt of the Doctor's degree was celebrated only recently. He is, without exception, the dean of glass chemists of all time.

Optical glass is made in a variety of ways. It may be melted in closed pots which are afterwards removed from the furnace and allowed to cool slowly. The various fragments are then sorted and utilized according to size and perfection. In the newer procedure, the glass is stirred mechanically to insure greater freedom from imperfections and the molten product is poured into molds of various sizes. Europe produced castings for astronomical lenses and reflectors up to one hundred inches in diameter. Recently, one American manufacturer has undertaken the production of a two-hundred inch reflector through an intricate process which has had so much publicity in the daily press that it does not require elaboration here. The first casting did not suit the manufacturers so a second one was made. This is now being annealed and will require over six months for complete removal of strains. Naturally, much greater detail in astronomical studies will result than has been available in the past. There has been some talk in the daily press of still larger reflectors, but we must remember that when the one of two hundred inches is crated it will clear the lowest railroad culvert by only eight inches and that it is not likely that larger castings will be made until they can be transported through the air to the Mount Wilson Observatory in California and others that may wish to use them.

The optical discussion thus far has covered material for the finer optical systems. We naturally think of the ordinary magnifying lenses, the somewhat finer glass for cameras and motion picture projectors and the blanks from which lenses are ground for spectacles or eye glasses. Some of these are pressed directly and the better ones ground and polished; others are even prepared by rolling the glass into a plate, cutting up into small sections and either melting in molds or grinding and polishing.

Though optical glass is usually thought of as a colorless crystal, for we carefully guard against the presence of iron in raw materials to insure the greatest transparency, there are special glasses for transmitting or absorbing certain radiations. These are also optical glasses. They include types for the transmission of ultra violet light in special lighting units, which range from transparent quartz to true glasses; apparatus for X-ray use; lead glass shields for protecting the operators against X-ray burns; goggle glasses, to protect against ultra violet and infra red radiations through their iron content; and still another type, which transmits ultra violet, but absorbs visible light, a glass containing nickel oxide.

Laboratory glass and *oven ware* should have a low thermal expansion and high resistance to mechanical shock. Ware of this type results from batches rich in boric oxide and silica and poor in other chemicals which cause a high expansion. These boro-silicate glasses are now a regular commodity. While considering laboratory ware, a word might be said about tubing, which is used so extensively not only in laboratories but in the manufacture of parts of electric lamp bulbs. Originally, tubes were prepared by hand. A workman gathered glass on his pipe, partially blowing a bubble and then having another workman attach an iron rod with a little soft glass to the lower end of the bubble. As the one operator continued to blow and the other walked away from him, the bubble became elongated and formed a tube whose diameter, wall thickness, and length depended on the amount of glass gathered and the method of manipulation. Glass tubing is now manufactured mechanically. In the Danner machine, the glass flows from the melting tank through a spout onto an inclined rotating fire clay cylinder. An iron pipe is attached

to the upper end of the cylinder. As the hot cylinder rotates and the glass flows upon it, gravitation naturally carries it to the lower end and as soon as it flows around the open bottom and runs together, air starts the bubble. An implement is attached to this bubble, which is carried away mechanically and as the glass is flowing constantly and the air is being introduced also, the bubble is drawn out as long as the mechanism operates.

Tubing is made from a bubble. If glass is drawn from a rod instead of a bubble, or is taken directly from the tanks and pulled away continually, fine threads form. These are gathered on rotating wheels with concave rims and constitute what is known as spun glass or *glass wool*. The fiber now manufactured is so fine that ten thousand threads will lie side by side in an inch space and a pound of glass would produce a thread long enough to reach from New York to San Francisco. Glass wool is employed in laboratories as a filtering medium and serves as an insulating material in refrigerators and other units where such insulation is required. The filters employed in air conditioning consist of glass wool which has been coated with an adhesive containing glycerin. The glycerin absorbs moisture from the air and the damp, porous mass removes dust particles from the air which passes through the filters.

Let us now consider *colored glasses*, such as those employed in lighting signals, table ware, art goods, etc. Considering these in the order of colors in the visible spectrum, or rainbow, we find that the reds were first produced by the use of copper compounds. The copper glass, when made under suitable conditions, comes from the pot as amber and upon reheating develops the red color. Gold compounds were later employed. These also produced a yellow to amber color which upon reheating developed a pigeon-blood ruby, rich in pink. Here the color is due to very small particles of gold which absorb practically all light except red. The particles are less than 1/100,000 of an inch in diameter. The newer reds owe their color to the element selenium, which again produces an amber glass and on reheating is converted to the ruby. Selenium rubies possess the advantage that the color is uniform with varying thickness and the amount of light

transmitted is high. They are ideal therefore for traffic signals. While the copper reds can be produced in lime or lead glasses, the selenium color requires a batch fairly rich in zinc oxide, and in addition to the selenium one must employ cadmium sulfide and other chemicals. If one uses a lime potash batch, selenium alone will yield a pink color; with cadmium sulfide in a soda lime glass, the color is orange. Amber glass is obtained through the use of charcoal, with sulfur or sulfur compounds. Yellows result in a variety of foundation batches through the use of silver or uranium compounds. The silver yellows are a true canary color, while the uranium glasses have a peculiar greenish fluorescence. Agents which produce green shades include iron, whose color is obvious when we look through a piece of window glass edgewise. This green color is one which manufacturers avoid in the finer types of glass, either through the purchase of specially pure raw materials or the introduction of decolorizing agents. Chromium compounds yield olive green glasses. With black oxide of copper, under oxidizing conditions, one may obtain shades varying from a light sky blue to a medium tone. Cobalt compounds give us the rich, deep royal blues. By proper apportionment of these substances which produce greens and blues, one can obtain almost any intermediate shade. The amethyst color results from the use of manganese dioxide, and the newer wisteria from the introduction of neodymium compounds into the glass batch. With the use of a sufficient quantity of either manganese or neodymium compounds, purples result, and these are even produced at times through the use of gold. Most black glasses that are on the market are not really black, for if you look through them at an intense light source, they appear purple. The blacks, therefore, result when chemicals which produce colors like the manganese amethyst or the cobalt blue are used in sufficient quantity. Opal and alabaster glasses are chiefly manufactured through the introduction of aluminum and fluorine compounds into the batch. They may have the ordinary opalescent, alabaster, or white appearance, or they may be colored with any of the substances mentioned for the production of the special colors. Control of the amount of coloring agent added will result in the production of almost

any color tone. In the Vatican Studios in Rome, where glass mosaics are produced, over fifty thousand color tones in glass are available. These colors are due to mineral compounds, or, in other words, inorganic chemicals, and are not to be confused with the various vegetable and coal tar dyes employed in coloring fabrics. The colors in glass are among the most durable that we have. To appreciate the variety available in glass colors, your speaker suggests that you either view the reproduction of Murillo's Immaculate Conception, which was prepared in the Vatican Studios for the Shrine of the Immaculate Conception in Washington, D. C., or the very attractive murals in the Union Station in Cincinnati.

The *treatment of glass* after it has been manufactured into what is known as units or blanks offers more than enough material for a separate lecture. Brief reference to it should, however, be made. One may etch glass with hydrofluoric acid alone or mixed with fluorides, and by properly coating the surface with a protective layer and working designs through this layer, etchings of various types result. One may also cut glass on abrasive wheels and by using finer and finer grades of abrasive, and finishing and polishing with rouge, produce brilliant facets or panels. When thin copper wheels are employed in various sizes, they yield the unusual engravings which are produced by many artists. Such effects may be obtained on a single type of glass or by taking a glass of two layers and cutting through or engraving the outer layer. Cameo glass, of which the Portland Vase in the British Museum is the outstanding example, has resulted from such treatment. Finally, enamels or softer glasses may be applied to the surface of the original piece and, by firing this lower melting material, produce art effects.

Before concluding this talk, a word might be said about *transparent fused quartz*, which, though not strictly a glass, has a glassy appearance. Most individuals have seen quartz crystals in the mineral collections of museums. An unusually pure variety comes from Brazil and is utilized in the laboratories of one of our large electric companies, where, after chipping off impurities, it is melted in electric furnaces to a non-crystalline transparent mass. This fused quartz can be

drawn into tubes or made into special apparatus of various shapes. I now place one end of a small, one-quarter inch rod, shaped like the letter S, behind a piece of black felt. You observe that the light from a flashlight travels through the rod and emerges at the other end of the S. Transparent fused quartz is the most transparent manufactured commodity that we have for visible light. It also transmits X-rays and ultra violet light, and X-rays will travel around the curves like the visible light. X-rays may, therefore, be carried to a particular point which is to be treated; for example, to an ulcer in the nasal pharynx. This transparent medium does not limit itself to the radiations already mentioned, but transmits infra red or heat rays equally well. When your speaker visited the laboratory of Elihu Thompson at West Lynn, Massachusetts, some years ago, a half-inch quartz rod about six feet long was mounted in his laboratory on a table. Some distance from one end there was a high-power tungsten lamp, with a conical reflector to concentrate the rays on the end of the rod. Half an inch beyond the other end, your speaker held a cigarette and got a light from the heat of the lamp filament. Transparent fused quartz is still quite expensive. The small S-shaped rod which you have seen cost several dollars. Day-dreaming is perhaps not a legitimate privilege of a lecturer, but your speaker ventures upon such a dream nevertheless. When he was a boy he read Jules Verne's "Twenty Thousand Leagues Under the Sea" and got quite a thrill out of the idea of being able to travel under the water. That imaginary submarine has become a reality. In his "War of the Worlds," H. G. Wells spoke of flying machines and the idea seemed equally wild. Now we have the dirigibles and the heavier-than-air craft. Now it so happens that the sand of the seashore consists of quartz grains, badly contaminated with foreign materials, to be sure; the day may come, however, when chemists will purify this sand cheaply and when electrical power will be cheap. When that day arrives, we should be able to manufacture transparent fused quartz as cheaply as we now make common glass. Assuming that time will arrive, we might expect to have a single powerful lamp bulb somewhere in the home and conduct the light through transparent quartz rods to the

various rooms. We might even lay heavy quartz conduits around the earth to light our cities with the sunlight from the opposite side of the globe. We could perhaps run the conduits north and south and dispel the chill of the Temperate and Frigid Zones with the warmth of sunlight from the Tropics. A wild dream perhaps, but others that have seemed equally preposterous, if not more so, have come true.

The title of this evening's lecture is "Glass: An Indispensable Factor in Modern Civilization." What have we had in the way of evidence to this effect? The audience can answer the question as well as the speaker. What should we do today without window glass to protect us against the elements in inclement weather? One can readily imagine what would happen to manufacture, or to all of us in our places of business and in our homes without the window pane. Plate glass makes possible the attractive displays in our shop windows and is utilized alone or with reinforcement in buildings and conveyances. The electric lamp bulb converts night into day. Through optical glass, we view the distant worlds of space and in the microscope study bacteria and the structure of materials. Optical glasses further correct the defects of human vision, affording normal sight to many of us. Optical lenses are used in the camera and motion picture machines and again in the projectors which instruct and entertain us. Special glasses serve a variety of scientific needs, and in glass tubing we seal and preserve the serums and anti-toxins for the prevention and combatting of disease. Watch and clock glasses protect our time pieces and insure the accuracy of the guiding compass for the mariner and the aviator. The endless array of colors gives us not only the attractive and ornamental glass of the home, but the decorative and even inspiring stained glass or art glass window and mosaic. These thoughts might be prolonged, but are already sufficient to convince the matter-of-fact populace that glass affords endless blessings and that it is really indispensable. What should we do without glass? Fortunately, we would not have the mirror to reflect our sorrow.

ELECTRICAL IMPEDANCE OF THE HUMAN BODY.

BY

J. W. HORTON, B.S., and A. C. VanRAVENSWAAY, M.D.,

From the Department of Electrical Engineering, Massachusetts Institute of Technology and the Metabolism Laboratory, Massachusetts General Hospital.

The significance of the impedance of living tissue to the passage of an electric current, as a physical quantity indicative of the condition of the tissue, has recently attracted considerable attention. The earliest attempts to measure the impedance of the human body [1] were carried out with direct current. Vigoroux, who reported on this work in 1888, believed that a correlation existed between thyroid activity and electrical conductivity. This measurement, however, encountered an almost insurmountable difficulty because of the polarization set up in the tissues. In 1919 Gildermeister [2] proposed to overcome this obstacle by using alternating current. In this case polarization is as definitely present as before, appearing now, however, in the reactance component of the impedance.

There are a large number of variables to be considered in measuring the impedance of the human body. It is necessary first to select the portion of the body which will be measured. This, in turn, involves the nature and method of application of the electrodes. Following this is the question of the frequency and the intensity of the alternating current—or of the impressed electromotive force. Having adopted a technique prescribing the above variables, and having completed a measurement, the data obtained are in terms of the resistance and the capacitive reactance of an equivalent electrical circuit. We may choose to consider this equivalent electrical circuit as having its resistive and capacitive elements in series or in parallel. In any case we must keep clearly in mind the fact that the equivalent circuit duplicates the electrical properties of the selected portion of the body, together with its electrodes, only insofar as it presents an identical impedance to the measuring apparatus.

A wide range in the variables mentioned above has been covered by various investigators who have given attention to this problem. The methods of measurement have also differed considerably. Wohl,[3] in Philadelphia, takes as the significant number the sum of the capacitances measured at different points on the body, using relatively small electrodes and an alternating current having a frequency of 1 KC. Rzherkin and Malov[4] determine the ohmic resistance between small electrodes applied to the palms of the hands, at a frequency of 450–500 KC. Finally, Brazier,[5, 6] in England, measures the tangent of the phase angle, using a frequency of 10 KC. and electrodes of the immersion type. All three investigators have reported a correlation between the measurement of their choice and different states of thyroid activity. Brazier describes changes produced in the measurement of normal individuals by thyroid and by thyroxin and an absence of change in those receiving a group of other glandular extracts. Rzherkin and Malof mention cases of asthma in which a deviation occurred similar to that which they found in hyper-thyroidism and described a return toward normal when the clinical condition of the patient improved.

At the present time an apparatus of the type described by Brazier is being offered for sale in England as a diagnostic instrument in thyroid diseases.

The present study received its initial impetus as a result of the published work of Dr. Brazier and began with an investigation of the particular technique suggested by her. This technique may be said to involve two features of major importance; first, the nature of the connection to the body and, second, the use of the ratio of the reactance to the resistance, each being measured in ohms, as the significant electrical constant. Dr. Brazier has called this constant the "Impedance Angle" and has designated it by the symbol ϕ. The ratio of the reactance to the resistance is not properly an angle but the tangent of an angle. Because of the magnitude of this angle as measured by Dr. Brazier there is little numerical difference between the angle and its tangent. It would appear preferable, however, to retain the notation already well established in electrical engineering and to designate this ratio by the quantity Q. Its use, as against that of certain of the

other quantities associated with impedance, has much to recommend it as it is a specific constant of the material involved and is not, in general, a function of the shape or quantity of this material.

With respect to the connection to the body Dr. Brazier has made an extensive study. Her procedure is to immerse the arms to the elbow in a saline solution of prescribed concentration and to make electrical connection by means of lead plates encircling the arms at a fixed distance. An advantage claimed for this method is that the portion of the body involved in the measurement is fixed with considerable accuracy and the condition of the electrical contact to the body is more or less reproducible. In our experiments, however, it was found that with the two arms immersed to the elbows there was considerable drifting, caused, apparently, by a combination of internal and external factors. In addition to a variability in the ease with which the skin is wetted, which is largely proportional to the amount of oil present, there are changes in the volume of the part immersed due to variations in the blood content. Because of the dependent position of the arm and the elimination of muscle action there is a slight and variable increase due to venous congestion. Vasomotor constriction or dilation, with a resultant change in blood flow also occur, according to the temperature of the saline solution. Although in our experiments an attempt was made to keep the immersing solution at, or near, body temperature, it was impossible to completely eliminate the drift, which frequently persisted for as much as thirty minutes. Certain other important factors entering into measurements made in this manner will be considered in detail later.

Having reviewed the essential features of Dr. Brazier's technique and checked her comprehensive study of the different variables involved as far as seemed warranted one question stood out as requiring further investigation. This was: how is the total impedance distributed between the surface sheath and the internal tissues of the body? This question has appeared in various forms in practically all of the recent investigations of the relation between body impedance and deviations from a normal condition. The importance of isolating the impedance of the skin, or the surface sheath, from

all the remaining large variety of tissues contributing to the total impedance lies in the fact that the skin appears more likely to be influenced by factors not associated with the condition of the tissues being studied. It is desirable, therefore, to know at least the order of magnitude of the contribution by the skin to the total impedance as measured by any given technique.

ELECTRODES.

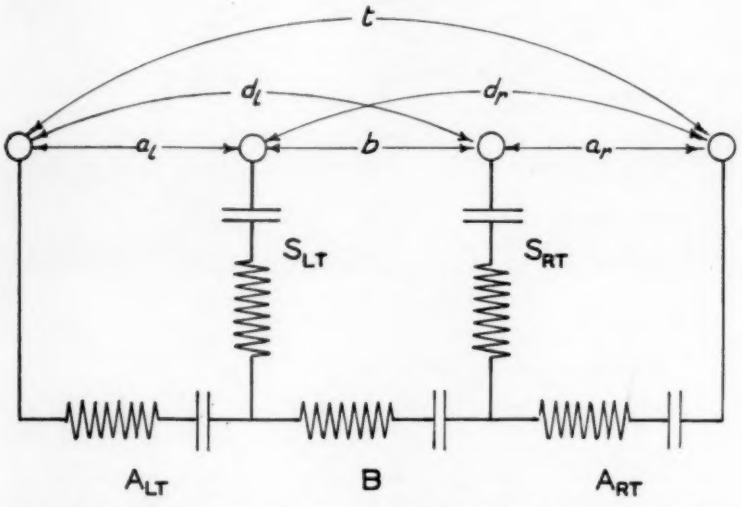
It is evident at the start that in attempting to measure definitely localized impedances it is imperative that the location and area of the electrode surfaces be fixed with considerable accuracy. After some experimenting an electrode was developed meeting the above requirements and offering at the same time decided advantages in the way of convenience. This electrode consists of a strip of 200-mesh phosphor-bronze wire screening, either 1.5 cm. or 3.0 cm. wide and roughly 45 cm. long. This is encased in a covering of "outing flannel" and is provided with a screw clamp fastening. The phosphor-bronze screening is soldered to the clip for electrical connection. In use the flannel is moistened in a one per cent. solution of sodium chloride.

IMPEDANCE OF SURFACE SHEATH AND OF INTERNAL TISSUES.

In our determination of the separate impedances of the internal tissues and of the external sheath four electrodes are placed on the arms of the patient; one on each upper arm and one on each wrist. It is clear that the resulting four-terminal electrical system may be represented by the network of Fig. 1. It is, of course, true that the junction of the current path through the surface sheath under one of the inner electrodes with the current paths through the internal tissues is not a point, as shown. Measurements indicate, however, that any error inherent in this assumption is small as compared with other inaccuracies in the measurement. By selecting, in turn, each of the six possible pairs of terminals various combinations of the several current paths may be measured and the separate impedances computed. It should be recalled here that when several impedances are connected in series the total impedance has a resistance component which is the sum of the individual resistance components and a reactance com-

ponent which is the sum of the individual reactance components. Therefore the resistance and reactance components of each current path may be determined by simple algebraic processes. Since there are six available groupings of these paths and only five paths, it follows that the impedance of any one path may be obtained from either of two sets of measurements. The relations between the several quantities are given in Fig. 1. Data taken from an actual set of measure-

FIG. 1.



Method for evaluating separately the impedances of the surface sheath and of the internal tissues.

S_{lt}, or S_{rt}, Impedance of surface sheath area under one electrode of inside pair.
B, Impedance of internal tissues between planes defined by inside pair of electrodes.
A_{lt}, or A_{rt}, Impedance between one electrode of outer pair and adjacent end of B. These impedances include the surface sheath under the outer electrode and the internal tissues between this electrode and the adjacent electrode of the inner pair.

$$S_{lt} = \frac{a_l + b - d_l}{2} = \frac{a_l + d_r - t}{2}$$

$$S_{rt} = \frac{a_r + b - d_r}{2} = \frac{a_r + d_l - t}{2}$$

$$B = \frac{b + t - (a_l + a_r)}{2} = \frac{d_l + d_r - (a_l + a_r)}{2}.$$

ments are given in Table 1. The agreement between the values of the impedance of a given path, as determined by different group combinations, is reasonable when we take into account the fact that the desired values are obtained as relatively small differences between the measured quantities.

TABLE I.

Specimen Measurement, by 4-electrode Method, of Impedance of Surface Sheath and of Internal Tissues.

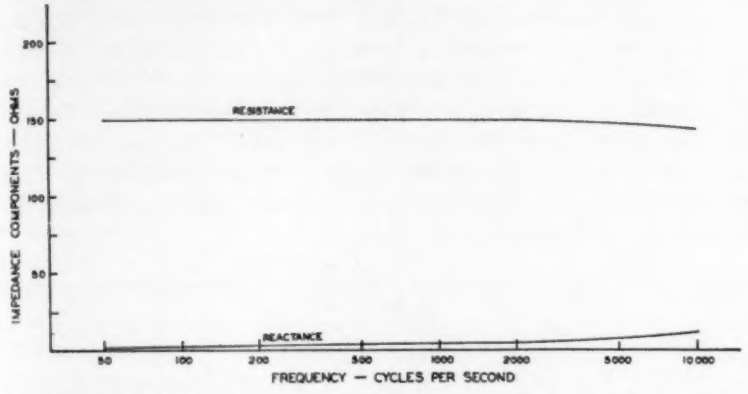
These measurements were made at a frequency of 10,000 cycles per second. The inner electrodes, under which the surface sheath impedances were observed, were 1.5 cm. wide. Reactance components are negative.

Measured values.	Resistance (ohms).	Reactance (ohms).
a_l	72.8	47.2
d_l	138.6	45.4
t	168.1	37.2
b	113.0	62.4
d_r	63.2	54.3
a_r		35.4
Surface sheath, left		
$\frac{a_l + b - d_l}{2}$	23.6	32.1
$\frac{a_l + d_r - t}{2}$	23.7	32.2
Surface sheath, right		
$\frac{a_r + b - d_r}{2}$	16.8	21.8
$\frac{a_r + d_l - t}{2}$	16.8	21.8
Internal Tissues		
$\frac{b + t - (a_l + a_r)}{2}$	72.6	8.5
$\frac{d_l + d_r - (a_l + a_r)}{2}$	72.7	8.6

IMPEDANCE OF THE SURFACE SHEATH AND OF INTERNAL TISSUES AS A FUNCTION OF FREQUENCY.

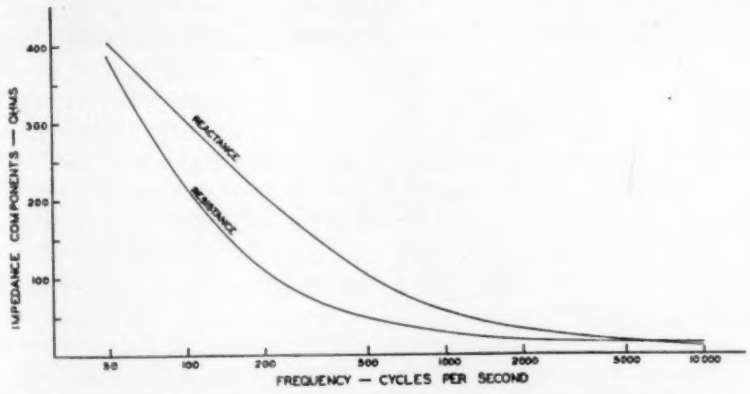
By means of the multiple electrode method thus described values for the impedance of the surface sheath and for the impedance of the internal tissues were obtained over a range of frequencies from 50 cycles per second to 10,000 cycles per second. Typical values of the reactance and of the resistance of a patient, as functions of frequency, are shown graphically in Figs. 2 and 3. It must be remembered that the values for the surface sheath apply to an area 3.0 cm. wide and completely encircling the arm; the values for the internal tissues apply to the entire portion of the body traversed by the current entering one upper arm, 10 cm. above the elbow, and leaving the other arm at a similar position.

FIG. 2.



Impedance of internal tissues of human body as a function of frequency. Measured between band electrodes on each arm, 10 cm. above elbows. Reactance component is negative.

FIG. 3.



Impedance of surface sheath of human body as a function of frequency. Measured under a 3.0 cm. band electrode encircling the arm 10 cm. above the elbow. Values shown are averaged from measurements on the two arms of a single patient. Reactance component is negative.

The components of the impedances of the internal tissues and of the surface sheath vary with frequency in a manner closely approximating that of circuits having fixed resistances and fixed capacitances connected in parallel. In the case of the fixed parallel circuit the impedance variations of which approximate those of the internal tissues, the magnitudes of the resistance and capitance are such that the reactance com-

ponent becomes equal to the resistance component at a frequency considerably higher than the highest frequency used in our measurements, namely, 10 kilocycles per second. On the other hand, in the case of the circuit the impedance variations of which approximate those of the surface sheath, the magnitudes of the elements are such that the reactance becomes equal to the resistance at a frequency lower than the lowest frequency used in our measurements, namely, 50 cycles per second.

IMPEDANCE OF SURFACE SHEATH AND OF INTERNAL TISSUES IN DIFFERENT PARTS OF THE BODY.

Having studied briefly the variation of impedance with frequency it was concluded that a frequency of 10,000 cycles per second was suitable for a consideration of some of the other variables. Attention was next turned to the relation between impedance and the position of the electrodes on the body. For this investigation the outer electrodes were fixed permanently at the wrists and the inner electrodes moved along the arm by 10 cm. increments. Measurements were taken (1) with the two inner electrodes always in corresponding positions, (2) with one inner electrode fixed and the other in each of the several positions along its arm and finally (3) with the two electrodes so placed as to measure each of the 10 cm. lengths of arm directly. These different methods of arriving at the variation of impedance with the portion of the body included between the inner electrodes agreed satisfactorily among themselves.

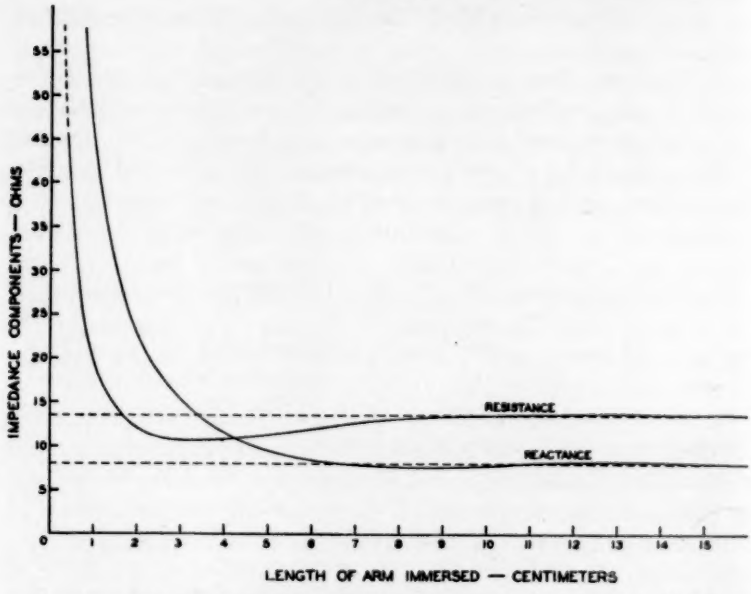
The resistance and reactance components of the impedance of the internal tissues show marked changes with the position of the inner electrodes—or with the portion of the body included—but there is little change in the ratio of these quantities, that is, in the constant Q. In fact in the majority of cases the value of Q for that portion of the body included between electrodes placed as near the shoulders as possible was practically the same as for a portion of the arm alone. This indicates, as Dr. Brazier has suggested, that the ratio of the reactance to the resistance may be considered a specific constant of the tissue, independent of the size or shape of the sample. It is evident, however, that this is by no means true

when the measured impedance includes both the surface sheath and internal tissues unless the contribution of the surface sheath is negligible.

With data taken as outlined above we have all the information necessary for accounting for the variation in impedance with varying degrees of immersion, as reported by Dr. Brazier. For example: with a given male patient it was found that the internal impedance, per centimeter length of arm, was approximately 4.5 ohms resistance and 0.45 ohm reactance. The surface sheath impedance, per centimeter length of arm, was approximately 25 ohms resistance and 45 ohms reactance. While these values vary appreciably with position along the arm it will be adequate for the present discussion to consider them as constants.

When the arm is immersed, as in Dr. Brazier's experiments, it is clear that the impedance of the immersed portion cannot be considered as made up of one surface sheath component and one internal tissue component, but that it must be treated as an infinite number of paths in parallel; each starting with a small area of surface sheath and continuing through internal tissues to the plane of the electrolyte surface. Systems of this general type, which are said to have "distributed constants," are common in electrical engineering and the technique for their computation is well established. Applying this technique we find that the impedance of the immersed portion of the arm of the patient on whom the measurements were made would vary with immersion as shown by the curves of Fig. 4. The only point of real significance to the present work is the fact that, for all immersions greater than 15 or 20 cm. the impedance between the electrolyte and the internal tissues immediately adjacent to the plane of the electrolyte surface is constant at approximately 13.5 ohms resistance and 8.0 ohms reactance. From this we see at once the part which the surface sheath plays in measurements made in accordance with the method proposed by Dr. Brazier. The impedance of the internal tissues between the planes of the two electrolyte surfaces is of the order of 300 ohms resistance and 30 ohms reactance. In impedances measured by the immersion technique, therefore, the resistance component differs but little from that of the internal tissues alone, being less than 10 per cent. greater.

FIG. 4.



Impedance of immersed arm as function of length immersed. Values apply to the impedance between electrolyte and internal tissues of unimmersed portion of the arm at the plane of the electrolyte surface. The curves are computed from average values of measured impedances of surface sheath and of internal tissues. Reactance component is negative.

The reactance component, however, is increased over 50 per cent. It is evident, then, that the ratio, Q, is greatly influenced by the condition of the surface sheath when immersion electrodes are used. It would appear desirable, particularly for a study of any possible relation between the impedance of the tissues and their condition, to adopt a technique which makes it possible to effect at least the rough separation between internal tissues and surface sheath accomplished by the above described 4-electrode method.

APPARATUS FOR DIRECT DETERMINATION OF BODY IMPEDANCES.

The multiple electrode method, although having considerable flexibility, is open to two major objections: it is cumbersome and tedious due to the large number of readings required and to the necessity for computation; it is inaccurate due to the fact that the desired values are obtained as small differences between relatively large quantities. To overcome these

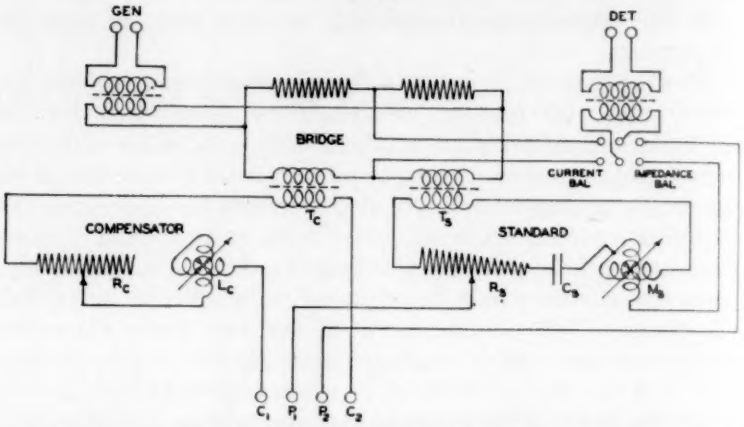
difficulties special measuring apparatus has been designed by which the desired impedances may be read directly from the dial settings.

This apparatus is essentially an alternating-current potentiometer with certain modifications adapting it for the direct determination of impedance. It provides for supplying current to the patient through the two outer electrodes of the 4-electrode arrangement. It also provides for independently supplying current to a standard circuit including a fixed resistance and the primary winding of a mutual inductometer. These two currents may be adjusted to be alike in magnitude and phase. The voltage between the two inner electrodes may be compared with a voltage made up of the drop across a portion of the fixed resistance of the standard circuit and the voltage induced in the secondary of the mutual inductometer. These two components are adjusted so as to make the two voltages alike in magnitude and phase. Since the two currents have already been made alike it follows that the impedances across which the two voltage drops occur must also be alike, hence the impedance between the two inner electrodes is the same as the impedance made up of the included portion of the fixed resistance and the mutual reactance of the inductometer. Inasmuch as no current flows through the inner electrodes when the known and unknown voltages are equal the impedance of the surface sheath under these electrodes has no effect on the measurement.

The general arrangement of the apparatus is shown in Fig. 5. Current from a suitable source of alternating current, such as a vacuum tube oscillator, is impressed on a bridge circuit comprising two equal resistance arms and the primary windings of two transformers which are as nearly alike as possible. The secondary winding of one transformer supplies current to the patient; the secondary winding of the other supplies current to the standard circuit.

It will be seen, from an examination of the circuit schematic, that the primary windings of the transformers, T_c and T_s, are in series with respect to the generator. Consequently the same current flows through each. If these were physically perfect transformers it would follow that the currents in the secondary windings would be alike also, in both magnitude and

FIG. 5.



Circuit schematic of impedance comparator. Two electrical paths through a network are connected to the apparatus; one to terminals C_1 and C_2, the other to P_1 and P_2. The impedance measured is that common to the two paths. The terminals of this common branch may be inaccessible for direct connection.

phase, and that our desired relation between the two currents would be satisfied. Due to the losses in the transformers, however, these secondary currents will be alike only when the transformers work into loads having equal impedances. To satisfy this condition a compensating impedance, including a variable resistance and a variable inductance, has been added to the load on the secondary of the transformer T_c in series with the patient. This compensating impedance may be adjusted to bring the impedances connected to the secondaries of the two transformers to the same value, with respect to both magnitude and phase. This will make the currents through them, independent of the losses, alike in magnitude and phase. When this condition is established the voltage drops across the primary windings will also be alike and the bridge circuit will be balanced. A detector connected as shown for "Current Balance," when brought to a zero reading by the adjustment of R_c and L_c, thus becomes an indicator for the required condition that the two currents be alike.

The detector may now be switched so as to respond to the difference between the voltages across the patient and across the standard impedance and the latter adjusted until the detector again indicates zero. As the mutual inductance

may be either positive or negative the sign of this second component may be either positive or negative. A reactive component obtained as the result of inductance may thus be made to equal the reactive component of the patient, which has the appearance of a capacitive reactance.

It should be noted that this second adjustment has no effect on the first as it does not alter the impedance connected to the secondary of the transformer T_2. This is because, when the two voltages are equal, no current flows in the detector circuit, hence the resistance is independent of the position of the slider and the reactance of the primary of the mutual inductometer is independent of the position of the secondary. Thus when the detector, connected as shown for "Impedance Balance," shows a zero reading we know that the resistance of the internal tissues of the patient, between the inner—or potential—electrodes, is equal to that portion of the resistance of the standard circuit included by the resistance adjustment. Similarly the reactance of the patient is equal to the reactance due to the mutual inductance obtained by the inductometer adjustment.

The capacitor, C_3, shown in the schematic permits an extension of the range of the mutual inductometer. The magnitude of the capacitor is such that its reactance is equal to the reactance of the mutual inductometer at maximum setting. With the inductometer set for maximum positive reactance, therefore, the total reactive component of the known voltage is zero; when set for maximum negative reactance the total component is twice that of the inductometer alone. The range of the instrument is thus doubled. As both positive and negative mutual inductances are used the scale length is also doubled.

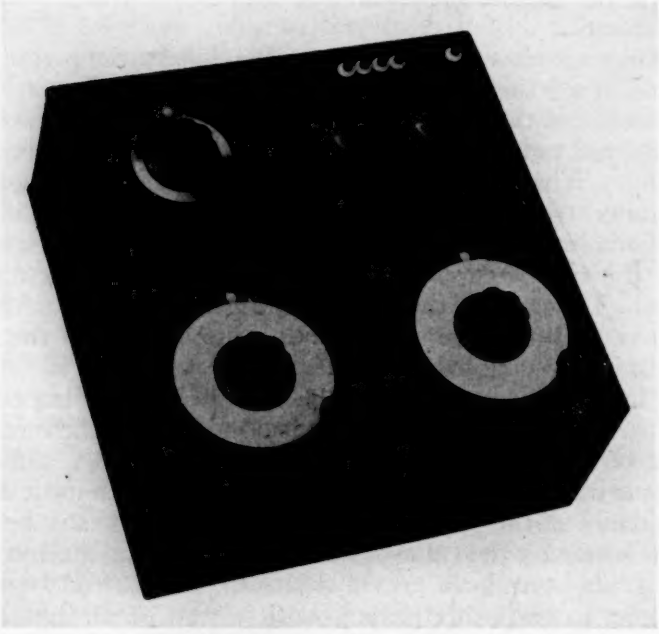
The above description of the operation of the impedance comparator has been, for simplicity, in terms of the measurement of the internal tissues of the human body. The apparatus may equally well be used for the measurement of the impedance of the surface sheath. In general it may be used for determining the value of the impedance of any path having inaccessible terminals provided this impedance can be made common to two other paths; one joining C_1 and C_2 and one joining P_1 and P_2. The impedances of branches external to

the common element have no effect upon the measurement. By grouping in various combinations the several paths contributing some given body impedance it has been possible to check individual measurements. In general it has been found that such checks show an agreement of about 0.1 ohm for both resistance and reactance.

In order to make the comparator direct reading the mutual inductometer has been calibrated in ohms reactance, $X_m = 2\pi fM$, for a frequency of 10 kilocycles. The instrument may be used at other frequencies and the reactance computed by multiplying the reading by the proper proportionality factor. In most cases, however, large excursions from 10 kilocycles lead to reactance values for which the range of the inductometer is unsuited.

The detector used with the impedance comparator consisted of a tuned 3-stage vacuum-tube amplifier followed by a

FIG. 6.



Impedance Comparator. Panel arrangement of apparatus shown schematically in Fig. 5.

copper-oxide-rectifier meter. Tuning was found to be necessary to avoid false balances resulting from harmonics of the impressed current generated in the tissues of the patient.

Apparatus embodying the circuit described above has been built in the form of a compact unit by the General Radio Company. A photograph, Fig. 6, shows the appearance of this finished instrument. This apparatus has been in use for some time at the Massachusetts General Hospital. Measurements made with it check closely with the results of bridge measurements on the several electrode pairs from which the impedances of the individual paths were obtained by computation.

CONCLUSIONS.

The preceding paragraphs have outlined a method, for use in the measurement of the impedance of living tissues, whereby the impedances of the internal tissues and of the surface sheath may be separately evaluated. A special form of electrode suitable for such measurements is described. From data taken by this method it has been possible to determine the contribution of the surface sheath and of the internal tissues to the total impedance of the human body as measured by the immersion technique. The results of this determination show clearly that the effect of the surface sheath is by no means negligible when considering the ratio of the reactance to the resistance components of the impedance as measured by the immersion method. It is suggested that measurements on the internal tissues alone are more likely to yield a significant indicator for diagnostic purposes than are measurements which include the effect of the surface sheath, particularly as the latter is, to a very considerable extent, accidental or, at best, arbitrary.

In preliminary studies carried out at the Massachusetts General Hospital an attempt was made to check the reported correlations between the so-called "impedance angle" and thyroid condition. Measurements were made of the internal tissues of the body included between band electrodes placed on the upper arms and of the surface tissues under these electrodes. Measurements were also made by the immersion method. Although the electrical data obtained by the two methods are consistent no evidence has yet been found that

the ratio of the reactance to the resistance, as given by either method, is a specific indicator for thyroid condition or that it can be substituted for a determination of the basal metabolic rate. A similar failure to establish this ratio as a thyroid indicator is reported in England by Robertson and Wilson [7], who have carried out an extensive and careful investigation using the direct reading apparatus described by Brazier, to which reference has been made earlier.

Although data as to the impedance of the human body appears not to be a specific indicator for thyroid condition it is apparent from the observed variations in impedance between individuals that the electrical impedance is related to their physical condition. The evidence of this is sufficiently convincing to justify a continuation of a study of the factors relating to the tissues of the body which determine the electrical impedance. It is hoped that such a study will indicate how, if at all, impedance measurements of diagnostic value may be made most effectively.

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THERMAL PROBLEMS IN THE MECHANICAL DESIGN OF STEAM TURBINES.

BY

RONALD BROMLEY SMITH, M.E.

INTRODUCTION.

Progress in the design of steam turbines has brought about marked decreases in thermal consumption. The internal efficiency of the turbine has been increased by improvements in the steam path and by reduction in mechanical losses through attention to detail. The rearrangement of the flow path, involving a study of fluid dynamics is promising and will undoubtedly receive emphasis in the future. Considerable attention has also been given to an improvement external to the turbine design proper, by employing the regenerative and the reheating cycles, as well as by increasing the operating pressures and temperatures.

Increasing the operating pressures, without a corresponding temperature rise introduces complications from moisture in the exhaust. Notwithstanding, pressures have risen so that large machines generally fall into either the 450–600 lb./in.^{2} or the 1,250 lb./in.^{2} design ranges. Moisture difficulties have been overcome by resuperheating, by adding moisture drains and by shielding the low pressure blades with materials that will resist erosion.

Definite increase in operating temperatures has been in abeyance through lack of knowledge of our engineering materials. Thermodynamically, however, this field possesses possibilities, for with a rise of only 60° F. in temperature, a decrease in heat consumption of about 2 per cent. is possible on a central station turbine. Design at present is centered about throttle temperatures of 850° F. with projected designs for as high as 1,000° F.

With the more severe operating conditions have come increased sizes and speeds. Whereas five years ago single cylinder units of 6,000 kw. were the limit at 3,600 r.p.m., it is not uncommon to design 10,000 kw. single cylinder units

for complete expansion at this speed today. Several 15,000 kw. turbines with back pressure exhaust have been constructed for 3,600 r.p.m., and capacities as high as 35,000 kw. in tandem arrangements with full expansion are contemplated. Single cylinder units for 1,800 r.p.m. have increased in size as well; notable is the recent 75,000 kw. turbine for the Public Service Corporation of New Jersey.

The increases in physical dimensions and in speed have only added to the difficulties resulting from higher pressures and temperatures, until it is evident on the basis of projected designs, that no problems are more significant than the mechanical design problems resulting from high temperature. These thermal problems fall into two classes. One type exists by virtue of the differential expansions that occur. Where the clearances are limited, as for instance along the blade path, or where displacements of the center of gravity may occur that will produce vibration, this type of problem is important. The other problem arises through the restrained thermal expansions, which frequently result in stresses that exceed the yield point. Problems in this classification are usually transient, and are frequently associated with starting or stopping, but since their effects are often permanent they cannot be underestimated.

MATERIALS AT HIGH TEMPERATURE.

Mechanical design at high temperature is handicapped by the changes that occur in the structure and in the physical properties of the engineering materials. Ludwik,[1] studying the problems of homology, found that the physical characteristics of many materials bear a relation to their absolute melting temperatures. At low homologous temperatures (the homologous temperature is defined as the ratio of the absolute temperature to the absolute melting temperature) most materials exhibit definite elastic and plastic regions. If plastic flow occurs immediately upon the application of load, it is so small in the elastic region that it can be neglected in comparison with the elastic strain. At higher homologous temperatures, materials obey more the laws of a viscous fluid, yielding continuously upon the application of load, under the lessening influence of strain hardening. The

lack of a definite transition point between plastic and elastic stages, accompanied by the fact that the plastic yield is frequently greater than the elastic strain has led to much confusion in the interpretation of high temperature test data.

At low homologous temperatures, for steel for instance the room temperature, the physical properties of most materials may be found from an ordinary tensile test; but at elevated temperatures the effect of viscous flow introduces a third variable, time. The property that materials exhibit toward a continuous plastic flow or creep as a function of time is becoming more important as the temperatures are raised on parts that must maintain dimensional stability. In addition to creep, physical changes are wrought in the internal structure, with the result that the short time tensile test must be supplemented by a long time test that will exhibit the true character of the material in service at elevated temperatures.

At normal temperatures the strength of few materials is affected appreciably by the rate of strain, $d\epsilon_p/dt = v$, except under the unusual conditions afforded by impact. Refined measurements, however, at normal temperatures by Ludwik,[2] Deutler[3] and Nadai[4] have shown that at any strain the strength does vary with velocity in such a manner that

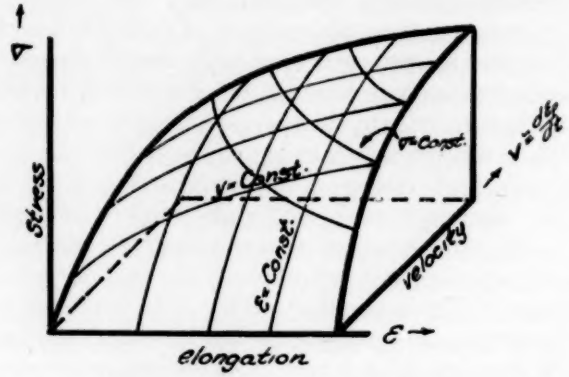
$$\sigma = \sigma_a + \sigma_b \ln \frac{1}{v_1} \frac{d\epsilon_p}{dt}, \qquad (1)$$

where σ_a, σ_b and v_1 are constants for the particular material. At elevated temperatures, as materials assume an amorphic character, the rate of strain becomes important. Bailey,[5] Prandtl[6] and others have found both experimentally and theoretically that Ludwik's equation represents a good approximation to the effect of velocity at elevated temperatures providing the strains are not too small. The addition of velocity introduces a three dimensional concept of strength, which may be represented as in Fig. 1 with

$$\sigma = f\left(\epsilon, \frac{d\epsilon_p}{dt}\right).$$

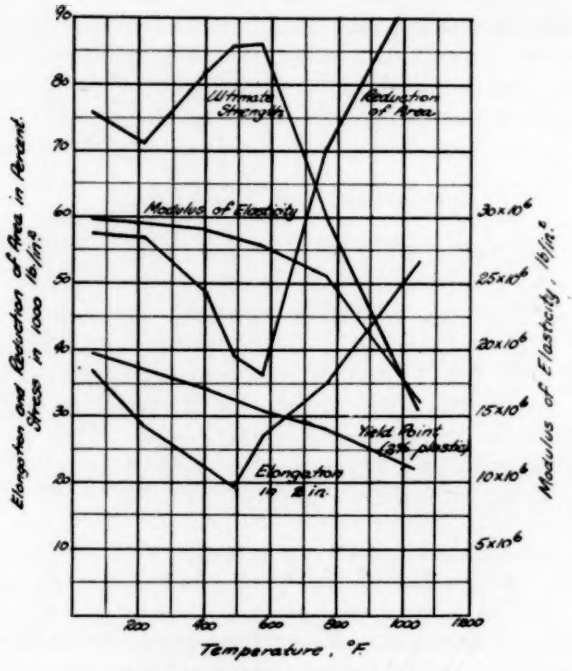
In Figs. 2 and 3 are shown the elastic properties of ordinary 0.37 carbon steel, and 12 per cent. chromium steel found

FIG. 1.



Three-dimensional concept of strength at elevated temperatures.

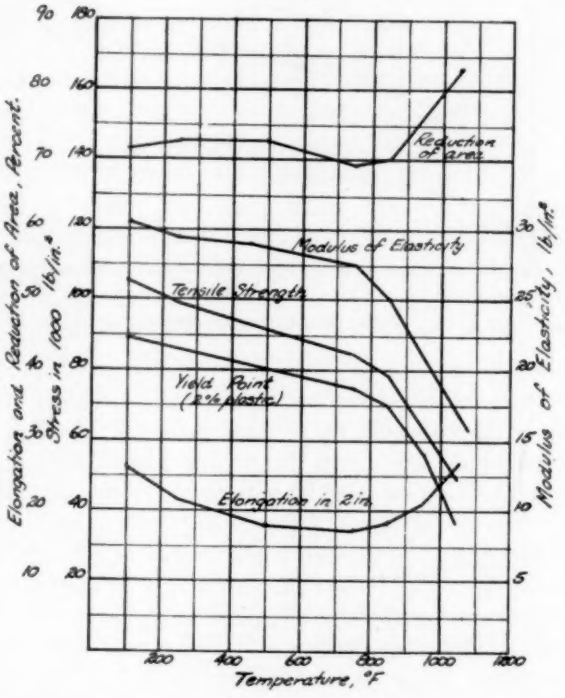
FIG. 2.



Physical properties of 0.37 carbon steel.

from short time high velocity tensile tests. The majority of steels exhibit reduction in strength, yield point and elastic modulus and an increase in elongation with temperature rise. Mild steels, however, increase in strength up until the "blue heat" region. Notwithstanding the influence of velocity, the short time tensile test is still the most satisfactory method of

FIG. 3.

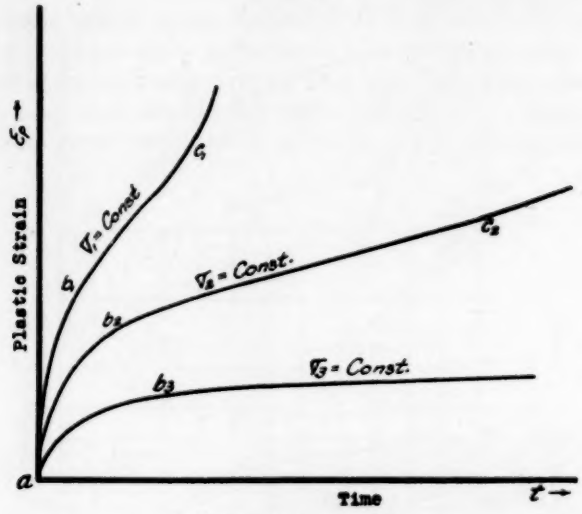


Physical properties of 12 per cent. chromium steel (C 0.10, Mn 0.45, Si 0.35, Ni 0.60, Cr 12.0).

obtaining the elastic properties of materials, but, unless the effect of creep is unimportant, caution should be exercised in interpreting the data.

In Fig. 4 are shown typical long time creep curves for a material at an elevated temperature. In general there are three stages in a plastic flow. The first stage *a–b*, occurs almost immediately upon loading and is characterized by a rapid reduction in the rate of flow as a result of work harden-

FIG. 4.



Typical long time creep curves.

ing. From b_1 to c_1 a more nearly constant flow rate exists, corresponding to semi-viscous behavior. In this region the annealing of the material by temperature and the increased resistance produced by strain hardening are in balance. At c_1 localized yield occurs, and the rate of creep increases until rupture. There is little information that establishes the points of inflection, c_1, c_2, but fortunately at the temperatures and stresses in vogue today the life of the material lies within the viscous region. For designs at constant stress the calculation of creep on the basis of a constant rate represented by the average slope of b_1–c_1 is satisfactory. In the design of pressed fits and bolts, where the load is dependent on strain, however, the initial stage must be considered.

The resistance of a material to creep is very sensitive to temperature. Strain hardening is reduced with increased temperature, until in some materials at 1,000° F. there appears practically no evidence of it. Similarly the viscosity, and so the resistance to deformation, of all viscous fluids is diminished with temperature.[7] The effect of temperature is so decided, that based on the present operating temperatures of 850° F. it is not infrequent to find that a

year's creep has occurred in some materials when they have been operated for merely a month at an increased temperature of 50° F.

Heat treatment is not generally beneficial in resisting creep when the temperatures are above 750° F., but at lower temperatures a quench from above the first transition point followed by tempering has shown beneficial effects. For high temperature service it is common to anneal the material. Cold working carbon or light alloy steels does not appear as beneficial at high temperatures as annealing. This follows from the fact that the ability a material possesses to maintain a high strain hardening effect with rising temperatures is a function of its freedom from internal stresses.

In designs where creep is important, alloy steels are used. The choice of alloy depends upon the temperature. For instance, nickel-chromium steel is satisfactory for low temperatures, but above 750° F. is disappointing, having properties no better than mild steel. Generally the addition of nickel is not beneficial in reducing creep when the temperatures are high; furthermore, nickel alloys have shown an inclination toward temperature embrittlement in long time service. The addition of about 1 per cent. molybdenum appears to result in a material that is resistant to creep up to 1,000° F., and vanadium in a limiting degree appears desirable too. Molybdenum steels have not shown signs of embrittlement. High chromium (stainless) steel has a low creep rate, has excellent elastic properties and in addition resists attack by chemicals and oxidation in a satisfactory manner. It is used for turbine blading, bolts and other parts that are subject to severe service. In Table I are compiled the creep resisting properties of several common alloy steels. Recently, austenitic-stainless steels have been employed, especially abroad. They appear to have attractive creep properties up to 1,100° F. and they resist oxidation, but in view of the fact that they develop intercrystalline cracks under certain service their application may be limited.

The creep properties of all materials are affected by changes in the internal structure; in fact few steels exhibit attractive long time properties above their first transition temperature. The addition of an alloy raises the recrys-

TABLE I.

Creep Resistance of Design Materials.

Material.	Composition.						Stress to Give Creep Rate 10^{-7} In./In./Hr.		
	C.	Mn.	Si.	Ni.	Cr.	W.	750° F.	840° F.	1020° F.
Car. Stl.	0.18							7,000	
Med. Car. Stl.	0.44	0.75	0.18				18,000	9,000	
Mn. Stl.	0.29	1.05						12,800	5,300
Cr.-W. Stl.	0.42	0.34	0.24		1.98	2.91		26,900	4,100
Ni. Stl.	0.31	0.83	0.16	3.42			12,000	4,600	
Cr.-Ni. Stl.									
12% Cr. Stl.	0.10	0.45	0.35	0.60	12.0		32,500	20,000	3,000
Cast Stl.	0.33						12,000	7,000	1,600
Cast Mn. Stl.	0.31	1.40	0.36					6,000	
Austenitic Steel.	0.10			8.57	17.25				15,200

tallizing temperature but this feature is still important since it is difficult to determine the critical temperature of an alloy steel accurately. Spheroidization of cementite has occurred in some steels at temperatures of 1,000° F. when in long time service. This phenomenon decreases the creep resistance, but if the material is well annealed previous to service, spheroidizing may be held in check. In addition, the tendency that many materials in high temperature service under strain have shown toward caustic embrittlement, corrosion, and intercrystalline cracking have necessitated consideration of these features as well in high temperature design.[8]

Notwithstanding the abundance of data for materials in tension, there exists but meager information for creep in shear and under compound stresses. Notable in these fields are the works of Everett [9] and R. W. Bailey.[5] The evidence indicates that creep occurs on all planes of shear, and is not influenced by the normal stresses on those planes. Until additional data are available, design will be based on the results of tensile creep tests; however, the frequent occurrence of combined stress systems warrant a more thorough investigation of this problem than has been possible heretofore.

TURBINE PROBLEMS CREATED BY THERMAL EXPANSION.

1. Mechanical Design of Parts Subject to Creep.

Mechanical design at elevated temperatures presents a double aspect. On the one hand is the problem of strength, while on the other there is the plastic problem of dimensional stability. Neither must the designer overlook the importance of part size and shape, for an excessively heavy section to reduce the stress and the creep frequently introduces the more insidious influences arising from material flaws or from excessive temperature gradients.

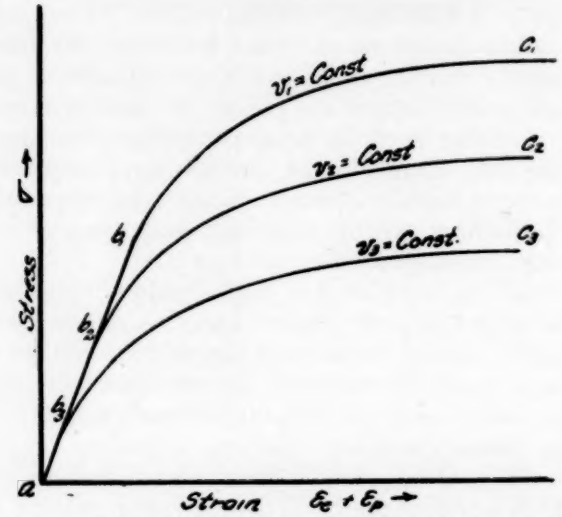
While the majority of our high temperature data emanate from long time creep tests and are reliable for applications under similar conditions, some rational method of extrapolation must be employed for the problems occurring under relaxation and at varying temperatures. At very low strain rates Ludwik's relation, equation (1), reduces to an absurdity, although at higher rates it has been verified by numerous investigations. The expression may be brought into line with modern experimental evidence which indicates that plastic strain occurs immediately on the application of load, by the addition of a constant term in the logarithmic relation so that

$$\sigma = \sigma_1 \ln\left(1 + \frac{1}{v_1}\frac{d\epsilon_p}{dt}\right). \qquad (1a)$$

The expression is not altered at higher strain rates by this addition.

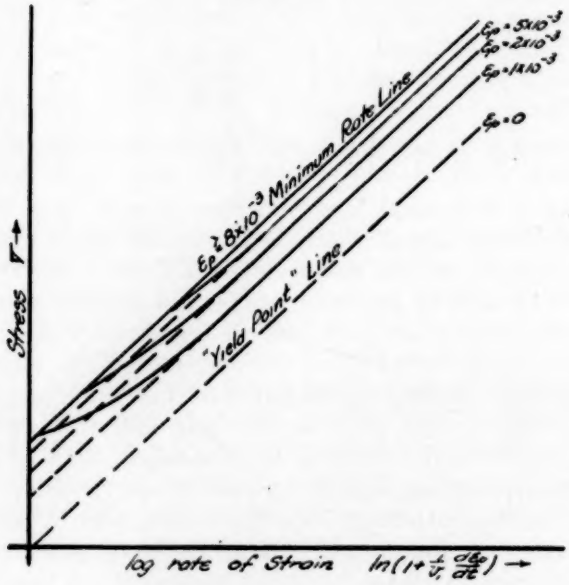
In Fig. 5 the usual long time creep tests have been replotted with velocity as a parameter and in Fig. 6 with strain as a parameter. At the lower values of strain rates the linear relation expressed by equation (1*a*) is not strictly adhered to. The point of inflection represents the transition from a viscous to a semi-viscous behavior in the material. The approximation in the low velocity region based on Ludwik's relation and shown dotted in Fig. 6 is on the safe side, and while not justified from a strict sense is reasonable in view of the uncertainty surrounding high temperature test results. On this basis the individual strain lines differ from each other by the strain hardening effect, and as the strain is increased the additional influence is lessened until it approaches a constant for

FIG. 5.



Stress–strain diagram for constant velocity at elevated temperatures.

FIG. 6.



Typical stress-strain-rate relation at elevated temperature.

all values of strain. This phenomenon is evidenced in Fig. 4 by a rapid initial flow rate, gradually decreasing through the region *a–b* under the work hardening influence until a constant rate represented by *b–c* results. The points b_1, b_2, b_3 corresponding to the velocities v_1, v_2 and v_3 in effect define new yield points for the material, under the specific temperature and velocity conditions, and are characterized by $\epsilon_p = 0$. The curve for $\epsilon_p = 0$ in Fig. 6 must be extrapolated from the existing data and is represented by equation (1*a*). The additional strength from work hardening, namely the region *b–c* in Fig. 5, may be approximated by $f(\epsilon_p)$, with the result that a relation for materials at elevated temperatures, may be written as,

$$\sigma = \sigma_1 \ln\left(1 + \frac{1}{v_1}\frac{d\epsilon_p}{dt}\right) + f(\epsilon_p). \qquad (2a)$$

The creep as a function of time or in some cases the relaxed stress as a function of time is then found from equation (2*a*) in the form

$$\frac{1}{v_1}\frac{d\epsilon_p}{dt} = e^{\frac{\sigma - f(\epsilon_p)}{\sigma_1}} - 1 \qquad (2b)$$

for the boundary condition, $t = 0$, $\epsilon_p = 0$.

In Fig. 7 long time creep tests are shown for 12 per cent. chromium steel at 850° F. The three variables σ, ϵ_p, and $d\epsilon_p/dt$ are represented in Fig. 8 with ϵ_p as a parameter. The relation expressed by equation (1*a*) fits the yield point line providing $\sigma_1 = 4{,}240$ lb./in.^{2}, and $\frac{1}{v_1} = 6 \times 10^6 s$. The strain hardening function is plotted from Fig. 8 and is represented in Fig. 9.

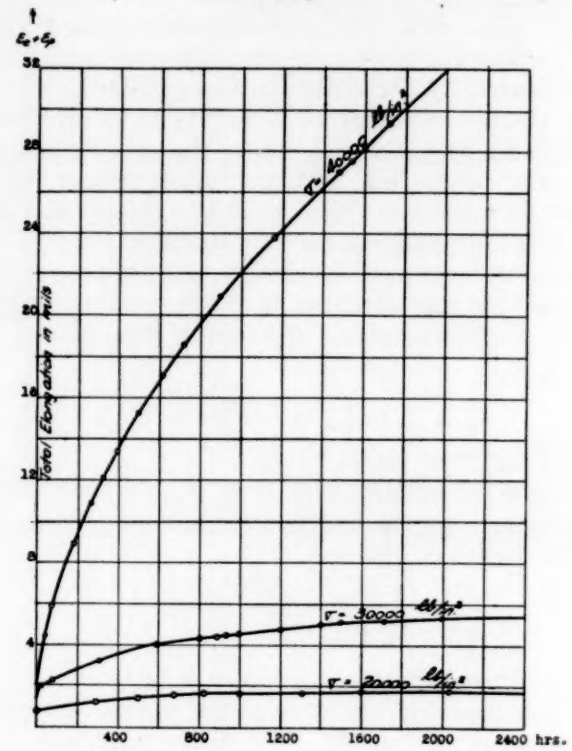
Problems at Constant Stress.

The problems in this group are characterized by $\sigma = \sigma_0 = \text{Const.}$ Equation (2*b*) may be written

$$t = \frac{1}{v_1}\int_0^{\epsilon_p} \frac{d\epsilon_p}{e^{(\sigma_0 - f(\epsilon_p))/\sigma_1} - 1}. \qquad (3)$$

In Fig. 10 are the results of a graphical integration of (3) for

FIG. 7.



Long time creep tests—chromium steel—850° F. (C 0.10, Mn 0.45, Si 0.35, Ni 0.60, Cr. 12.0.)

chromium steel. The agreement between analysis and test serves to justify the approximations in the general treatment of the high temperature design problem.

In the usual long time installation at constant stress, the creep is sufficiently large to neglect the initial stage and assume $f(\epsilon_p)$ a constant. Equation (2*b*) reduces immediately to

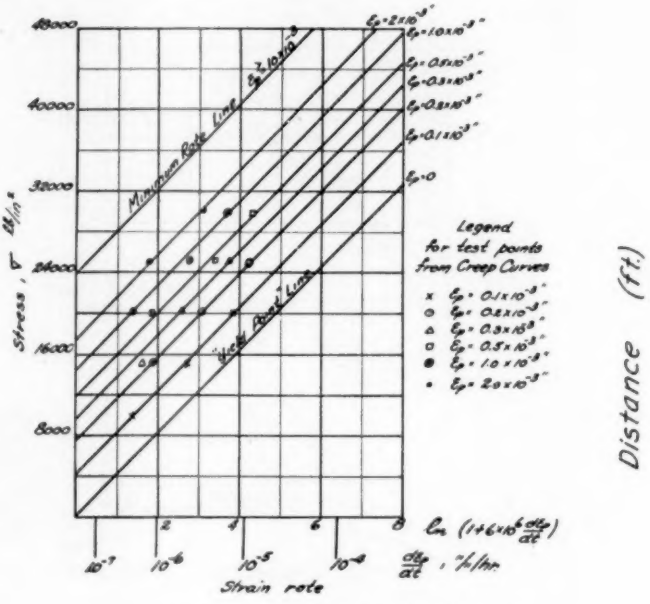
$$\frac{d\epsilon_p}{dt} = v_0 = \text{Constant} \tag{4a}$$

and

$$\epsilon_p = v_0 t, \tag{4b}$$

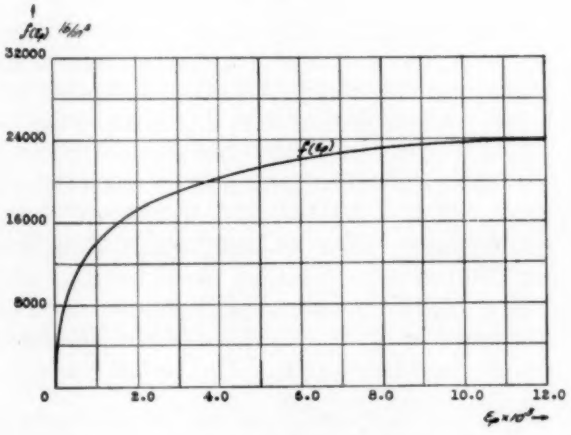
the well known relation expressing creep as the product of a

FIG. 8.



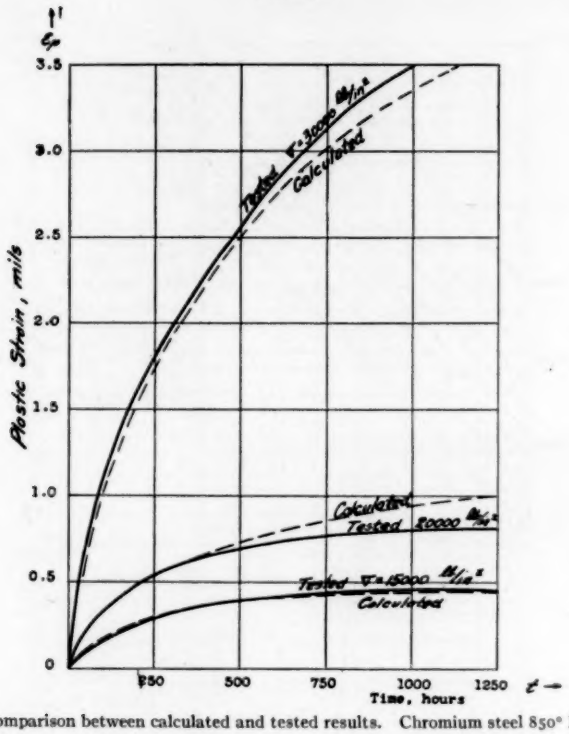
Stress-strain-rate relation for chromium steel 850° F.

FIG. 9.



Strain hardening function for chromium Steel—850° F.

FIG. 10.



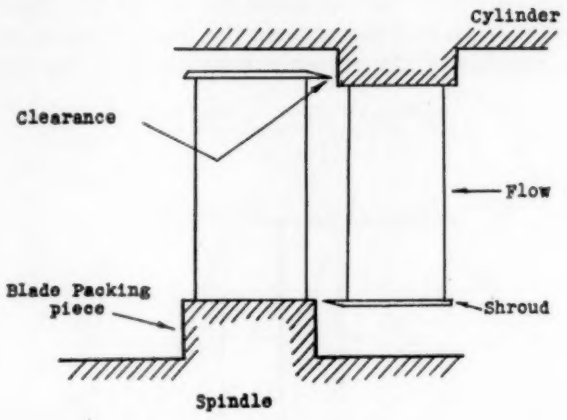
Comparison between calculated and tested results. Chromium steel 850° F.

constant creep rate and time. This constant rate is represented by the region *b–c* in Fig. 4 and at higher stresses by the minimum rate line of Fig. 8. For extrapolating to lower rates of strain the minimum rate line stress may be plotted against $\log_{10} v_0$. Equation (4*a*) is equivalent to viscous flow.

The radial creep of spindles is a typical example of viscous flow. Here, the relative movement between the spindle and cylinder must be kept within close limits, since any serious displacement between the stationary and moving elements of a typical reaction stage shown in Fig. 11 will lower the internal efficiency by the introduction of additional eddy losses at the blade inlet. The radial creep is reduced by keeping the average stress low.*

* Creep may be based on the average stress and not the maximum, since any non-uniform stress distribution is rapidly reduced to a uniform one through the fact that the flow is proportional to the stress.

FIG. 11.



Axial tightened reaction blades.

Problems at Constant Strain.

The tightness of a bolted joint is relieved as continued plastic flow occurs in the bolt material at elevated temperatures. This relaxation would continue until the stresses become zero were it not for the strain hardening influence. The increased resistance to flow offered by the slip of the crystals results in a practical limit to the value of the relaxed stress. Although a function of the stress to which the joint is initially tightened, the time for the relaxation to occur is surprisingly short.

An analysis of the relaxation problem in bolts involves a consideration of the creep of the flanges and the elasticity of the flange material. Generally the former is small, whereas the latter may be represented as an additional spring effect. Schematically the relaxation problem in a bolt may be represented by Fig. 12. Using an equivalent modulus of elasticity,

$$E' = E\left(\frac{1}{1 + \frac{aE_b}{A_f E_f}}\right),$$

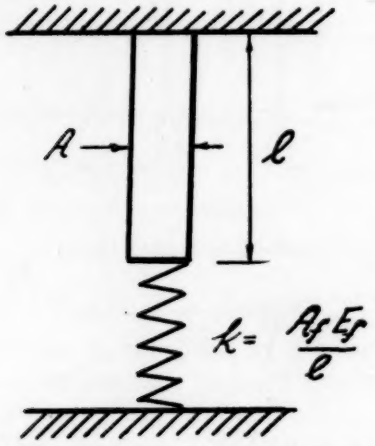
the usual elastic equations may be employed. The modulus of the bolt E_b and that of the flange E_f are frequently the same

but the ratio of areas a/A_f is usually so small that $E' = E$. In any case the decrease in modulus serves to lengthen the time for relaxation and to increase the final value of stress.

Characteristic of the relaxation problem is the expression

$$\epsilon_0 = \epsilon_e + \epsilon_p = \text{Constant}.$$

FIG. 12.



Schematic representation of relaxation in a bolted flange.

Referring to Fig. 13 the relaxed stress after any plastic strain ϵ_p is represented by

$$\sigma = \sigma_0 - E'\epsilon_p + f(\epsilon_p) \tag{5a}$$

where σ_0 is the initial stress. Substituting in equation (2a), the $f(\epsilon_p)$ may be eliminated and the solution becomes

$$t = t^* \ln \frac{1 - e^{-\sigma_0/\sigma_1}}{1 - e^{-(\sigma_0 - E'\epsilon_p)/\sigma_1}}, \tag{6a}$$

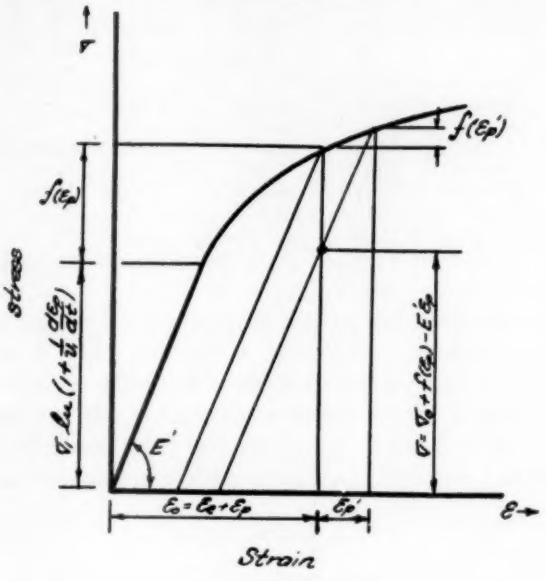
where $t^* = \sigma_1/v_1E'$. The strain is given by the expression,

$$\epsilon_p = \epsilon_0 - \frac{\sigma_1}{E} \ln \frac{1 - e^{-\sigma_0/\sigma_1}}{1 - e^{-t/t^*}} \tag{6b}$$

and the relaxed stress from equation (5a) and the $f(\epsilon_p)$.

At infinite time equation (6a) is satisfied by $\sigma_0 - E'\epsilon_p = 0$ or $\epsilon_p = \epsilon_0$, in which the creep equals the initial elastic strain.

FIG. 13.



$\sigma - \epsilon$ diagram in relaxation.

Under these conditions the stress does not reduce to zero but is from equation (5*a*),

$$\sigma = f(\epsilon_p) = f(\epsilon_0). \tag{5b}$$

Thus the effect of strain hardening within the material tends to maintain the bolt under load even though the time be extended and the creep $\epsilon_p = \epsilon_0$.

At high temperatures, for instance in stainless steel 850° F. or above, the ratio of σ_1/E', and $\epsilon_0 = \sigma_0/E'$ in the usual design range is small due to the reduced σ_1, and the parameter t^* is also small compared to t over a period of months. The relation (9*b*) may then be approximated by

$$\epsilon_p \cong \epsilon_0$$

and the relaxed stress becomes as in (5*b*),

$$\sigma^* = f(\epsilon_p) = f(\epsilon_0). \tag{5c}$$

In Table II a comparison of the relaxed stress in a 12 per cent.

TABLE II.

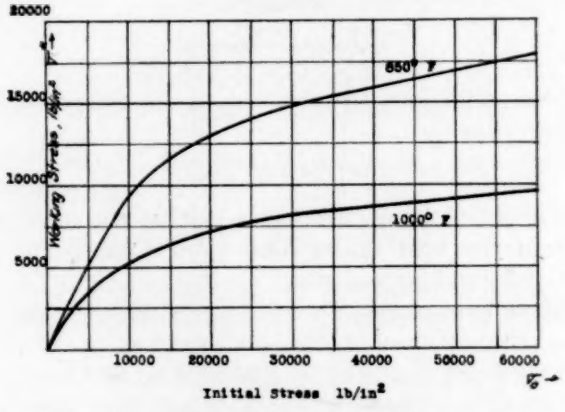
Relaxation in a 12 Per cent. Chromium Steel Bolt at 850° F.

Initial Stress, lb./in.²	σ*, Relaxed Stress, lb./in.²					
	500 hrs.	1,000 hrs.	1,500 hrs.	2,000 hrs.	3,000 hrs.	5,000 hrs.
30,000	18,400	16,700	15,800	15,500	15,100	15,000
45,000	20,100	18,300	17,400	17,200	16,700	16,500
60,000	21,500	19,600	18,700	18,450	18,000	17,800

chromium steel bolt at 850° F. is made for various values of initial stress.

The real significance of the expression $\sigma^* = f(\epsilon_0)$ is that it defines the working stress for a bolt in high temperature service. It is the stress to which the bolt is relaxed in a period of from 1,000–2,000 hrs. and which it retains for an indefinite time. Under this stress the joint must be designed for tightness. In Fig. 14 the working stress for chromium

FIG. 14.



Working stress for chromium steel bolts—850° F.–1,000° F.

steel bolts at 850° F. and 1,000° F. is shown as a function of initial stress.

The beneficial effect of strain hardening is even more pronounced on retightening * the joint, for the total strain be-

* This phenomenon was first pointed out by Mr. C. R. Soderberg in "Working Stresses," A. S. M. E., 1932.

comes the sum of the strain in the first relaxation ϵ_{p_1}, and that in the second ϵ_{p_2}. Equation (2*a*) is readily modified for this condition,

$$\sigma = \sigma_1 \ln\left(1 + \frac{1}{v_1}\frac{d\epsilon_p}{dt}\right) + f(\epsilon_{p_1} + \epsilon_{p_2}), \qquad (2c)$$

in which the stress is

$$\sigma = \sigma_{0b} + f(\epsilon_{p_1} + \epsilon_{p_2}) - f(\epsilon_{p_1}) - E'\epsilon_{p_2}, \qquad (2d)$$

when σ_{0b} is the reëstablished stress in the bolt. The solution to (2*c*) yields

$$t = t^* \ln \frac{1 - e^{-\sigma_{0b}/\sigma_1}}{1 - e^{-(\sigma_{0b} - f(\epsilon_{p_1}) - E'\epsilon_{p_2})/\sigma}}. \qquad (6c)$$

At high temperatures the relaxation is so rapid that (2*a*) may be approximated by the working stress,

$$\sigma^* = f(\epsilon_{p_1} + \epsilon_{p_2}) \qquad (5d)$$

with

$$\epsilon_{p_2} = \frac{\sigma_{0b} - f(\epsilon_{p_1})}{E'}.$$

As an example consider a chromium steel bolt for 850° F. service tightened initially to 50,000 lb./in.^{2} and then after 1,500 hours service retightened to 40,000 lb./in.^{2}. The initial extension is,

$$\epsilon_{p_1} \leqq \epsilon_{p_0} = \frac{\sigma_0}{E'} = \frac{50{,}000}{25 \times 10^6} = 2 \times 10^{-3}$$

with the subsequent extension,

$$\epsilon_{p_2} = \frac{\sigma_{0b} - f(\epsilon_{p_1})}{E'} = \frac{40{,}000 - 17{,}000}{25 \times 10^6} = 0.92 \times 10^{-3}.$$

The working stress for the joint is now

$$\sigma = f(\epsilon_{p_1} + \epsilon_{p_2}) = 18{,}800 \text{ lb./in.}^2$$

as compared to 17,000 lb./in.^{2} originally.

2. Spindle Distortion Resulting from Eccentric Bore.

Specifications for large spindle forgings usually require that an axial hole be drilled in the center of the mass for inspection purposes. As a result of the extreme length of modern

turbine spindles it has become increasingly difficult to drill the forging without some eccentricity. Erratic behavior of turbines in service, especially in respect to transient vibrations, has been attributed to distortion by a non-uniform radial temperature distribution as a result of bore eccentricity. This has resulted in imposing rigid requirements on the steel mills in regard to the truth of the bore. In an effort to place the specifications for spindle forgings on a rational basis an analysis of the possible distortion as a result of eccentricity is of interest.

The treatment of the problem is rather complex unless some simplifying assumptions are made regarding the temperature distribution and the unbalanced forces. In cases in which the outer and inner temperatures are fixed, a condition found on spindles near the gland surfaces when there is internal circulating steam, the temperature distribution follows the well known logarithmic relation. Spindles having no internal circulating steam, but which are subject to sudden changes in temperature with load, for instance the exhaust end of a high pressure machine operating in tandem with low pressure turbines, are also subject to transient disturbances from non-uniform temperature distribution. In this case the radial temperature function is found from an analysis involving Bessell's relations.[10] It changes rapidly with time from a semi-logarithmic relation to a near linear function. In any case the logarithmic distribution involves a more severe distortion for a given temperature difference than the linear expression.

Consider at first a cylinder of uniform bore with an inner radius r_1, an outer radius r_2, and with a temperature difference between the outer and inner surfaces represented by θ^*. By neglecting the complexities introduced in the transient state, the radial temperature distribution may be found from a solution to the continuity equation,

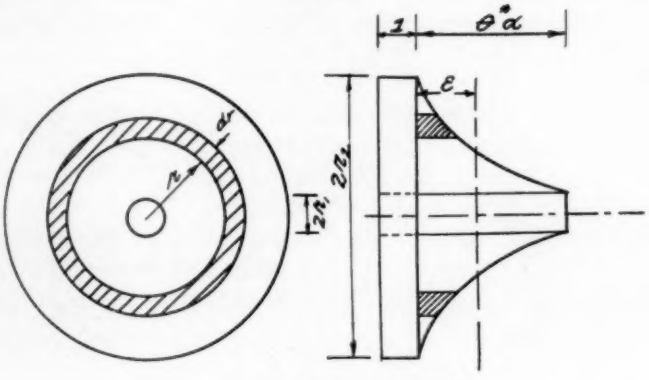
$$\frac{d}{dr}\left(r\frac{d\theta}{dr}\right) = 0 \qquad (8a)$$

that satisfies the boundary requirements. If the temperature is higher at the inner radius the solution becomes

$$\theta = \theta^* \frac{\ln r/r_2}{\ln r_1/r_2}. \tag{8b}$$

Under the action of (8*b*) the spindle is subject to local expansions in the axial direction, see Fig. 15*a*, with a re-

FIG. 15*a*.



Axial elongation of a turbine spindle.

sulting average elongation per unit length of ϵ. The force acting on the section $2\pi r dr$, neglecting the effect of shear, and created by restrained thermal expansion is

$$dp = 2\pi r dr E \left(\theta^* \alpha \frac{\ln r/r_2}{\ln r_1/r_2} - \epsilon\right).$$

The unit extension of the body ϵ, under the action of the temperature field, is determined from the condition that satisfies the equilibrium state, namely,

$$\int_{r_1}^{r_2} dp = 0$$

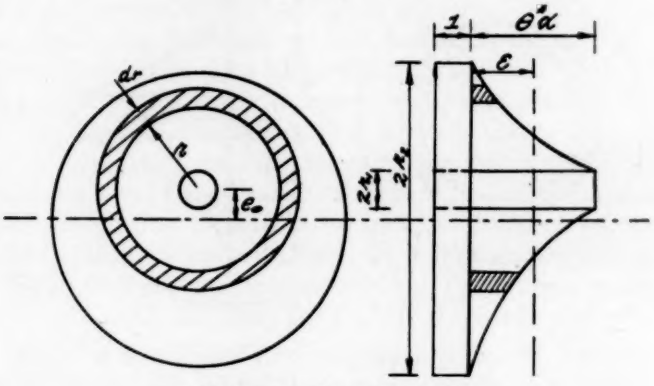
or

$$\epsilon = \frac{\alpha\theta^*}{2 \ln r_2/r_1} - \frac{r_1^2 \alpha\theta^*}{r_2^2 - r_1^2}. \tag{9}$$

Under these conditions the temperature distribution is uniform, the forces are balanced, and there is no resulting moment tending to distort the spindle.

Returning to the case of an eccentrically bored cylinder, Fig. 15*b*, with the assumption that the eccentricity is not sufficient to alter the logarithmic distribution of temperature, it is evident that the force on the innermost differential ring concentric with the axial hole will produce a moment about the neutral axis of magnitude $dp \times e_0$. The bending moment for the outer ring will be negligible since e_0 is small compared to r_2. The exact variation of the moment throughout the

FIG. 15*b*.



Axial elongation of a turbine spindle.

piece is uncertain, but a satisfactory approximation is possible on the assumption that the eccentricity varies linearly from the center in such a fashion that

$$e = \frac{r_2 - r}{r_2 - r_1} e_0.$$

The bending moment on the cross section is

$$M = \int_{r_1}^{r_2} dp e_0 \frac{r_2 - r}{r_2 - r_1}, \tag{10a}$$

which produces a curvature ρ in the cylinder of

$$\frac{1}{\rho} = \frac{M}{EI} = \frac{\alpha\theta^* e_0}{r_2^2} f\left(\frac{r_1}{r_2}\right). \tag{10b}$$

Values of $f(r_1/r_2)$ are tabulated below.

$$\frac{r_1}{r_2} = 0.1 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8$$

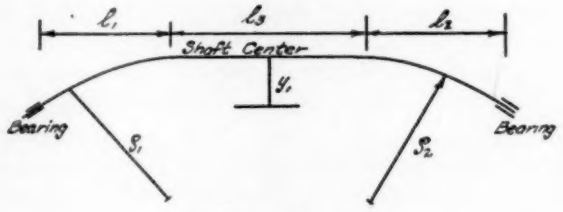
$$f\left(\frac{r_1}{r_2}\right) = 0.16 \quad 0.24 \quad 0.26 \quad 0.235 \quad 0.20$$

For the usual ratio of radii, $f(r_1/r_2)$ is near the maximum of 0.25, which gives for the radius of curvature the relation

$$\frac{I}{\rho_{max.}} = \frac{I}{4}\frac{\alpha e_0}{r_2^2}\theta^*. \qquad (10c)$$

Of real importance is the distortion of the mass center of the rotating body by the curvature (10*b*). This effect depends on the length over which the curvature acts and the general characteristics of the spindle. The worst possible case assumes equal distortion at both high and low pressure glands. Under these conditions the mass displacement can be represented with not too great an error (see Fig. 16) by $y_1 = l_1^2/2\rho_1$.

FIG. 16.



Deflection of turbine spindles.

This deflection creates a reduction in radial clearances as well as unbalanced dynamic forces. In general the reduction in clearances is not sufficiently great to produce body or blade rubs, but the displacement of the mass center may result in undesirable vibration, especially in the case of three bearing machines where the eccentricity of the turbine reacts on the generator rotor. Whether the amplitude is severe depends upon the design characteristics of the unit, for instance the location and magnitude of the mass center, and the general elastic properties of the rotor, the pedestals and the foundation.

As an example consider the deflection of a typical spindle

for high temperature service having an eccentric bore at the labyrinth glands. The following dimensions are normal, $r_2 = 3\frac{1}{2}$ in., $r_1 = 1$ in., $\theta^* = 200°$, $l_1 = 30$ in., and $e_0 = 0.025$ in.

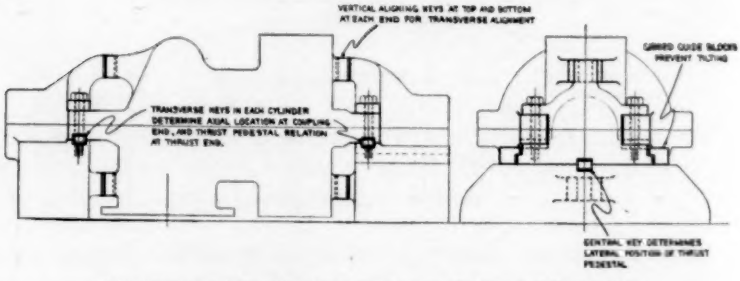
$$y_1 = \frac{l_1^2 \alpha e_0}{8 r_2^2} \theta^* = 0.000367 \text{ in.}$$

To rationally predict a safe eccentricity is impossible, but relying on past experience it is probable that $y_1 \leqq 0.0005$ should not create undesirable dynamic effects in any normal turbine. In view of the above result it is probable that forging specifications have been more strict than necessary in the matter of eccentric bore.

5. Relative Axial Expansion Between Cylinder and Spindle.

Considerable difficulty has arisen in past years in providing for unrestrained expansion of stationary turbine parts, especially in high temperature design where the overall movements may be as great as 1/2 in. In Fig. 17 is shown a

FIG. 17.


VERTICAL ALIGNING KEYS AT TOP AND BOTTOM AT EACH END FOR TRANSVERSE ALIGNMENT
GUIDED GUIDE BLOCKS PREVENT TILTING
TRANSVERSE KEYS IN EACH CYLINDER DETERMINE AXIAL LOCATION AT COUPLING END, AND THRUST PEDESTAL RELATION AT THRUST END.
CENTRAL KEY DETERMINES LATERAL POSITION OF THRUST PEDESTAL

Cylinder supports to allow for expansion on a single cylinder turbine.

successful system of keying the cylinder at the exhaust end, at the same time allowing it to expand by sliding on guides at the thrust end as it drags the spindle back with it. With suitably placed keys the whole cylinder is free to move without resistance from the exhaust or inlet pipe lines, thus eliminating the undesirable consequences of warped cylinders or bowed spindles when the machine is in operation.

The most recent high temperature designs have employed axial clearance reaction blading as shown in Fig. 11. With

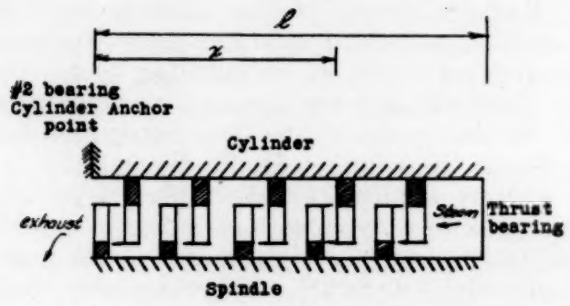
the spindle carried from the thrust bearing, which is suspended in a cage movable through a worm and hand wheel drive, the rotor may be shifted axially in respect to the cylinder and the clearances can be changed at will. This is distinctly advantageous since the machine may be backed off to greater clearances during the critical starting or stopping periods and drawn up for highly efficient performance during the operating periods. Radial clearance blading offers no such flexibility and in addition an added clearance must be provided to eliminate the possibility of devastating body rubs when starting. Axial rubs are less harmful inasmuch as the wear occurs on the thin section of the shroud strip and the heating does not distort the spindle. Hydro-dynamically, it is questionable whether the axial clearance blade is as efficient as the radial clearance type with identical clearance areas, since the leakage flow is at right angles to the main stream flow and the eddy effects are more pronounced; but in view of the possibility of operating at clearances of only 0.010 in.–0.015 in. there is much in favor of the former. Machines of the axial clearance type are "ground in" immediately after they have been placed in service and have become thoroughly heated, by drawing the spindle up to a rub on the cylinder and grinding the shrouds down until there is uniformity throughout.

It is important that the spindle and cylinder materials have similar thermal characteristics in order to prevent serious differences in their relative expansions. Even then, there may be difficulty unless the cylinder and spindle are at the same temperature. Seldom is this condition realized inasmuch as there are losses through the lagging, but fortunately this displacement is remedied when the turbine is ground. Transient periods in which there is relative movement also occur during load changes, because the cylinder will usually respond less rapidly to a temperature rise than the spindle. Particularly is this true on high temperature back pressure turbines where exhaust temperature changes as great as 150° are not uncommon.

Since the cylinder is generally at a lower temperature than the spindle, it is desirable to build the machine with axial blade clearances when cold, progressively greater from the

exhaust to the dummy pistons, so that when the spindle and cylinder are at operating temperatures the resulting clearances may be more nearly uniform. With the spindle and cylinder of an axial tightened machine represented schematically in Fig. 18 the change in clearance at any blade group, created by

FIG. 18.



Schematic arrangement of axial tightened reaction turbines.

temperature distribution in the two parts, is given by

$$\delta = \int_x^l (\theta_c - \theta_s)\alpha dx, \tag{11}$$

where θ_c and θ_s are the temperature of the cylinder and spindle as function of the length and α the coefficient of thermal expansion.

Considerable effort has been expended by manufacturers to gather evidence on the axial temperature distribution in turbines from thermocouple measurements; with the result that it is now possible to predict the probable temperature difference between spindle and cylinder with allowances for the influence of impulse elements, back pressure exhaust and methods of lagging. For an 18,000 kVA turbine operating at 850° F., 600 lb./in.^{2} and with a back pressure of 205 lb./in.^{2}, the cold clearance on the high pressure end may be increased as much as 0.010 in. Employing this expedient, the relative expansion is partly compensated and the turbine may be ground to uniform clearance without removing a large portion of the high pressure shroud strips before the low pressure blades begin to rub. Under any conditions grinding turbines

is a delicate task and any method to bring about more uniform running clearance with the minimum grinding is desirable.

4. Pressed Fits.

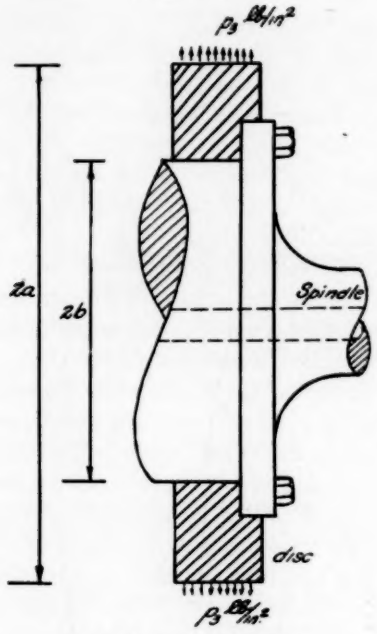
In recent years the forgings for large turbines have become so massive that good design has dictated the construction of the spindle in more than one piece; not alone from the standpoint of economy, but from the standpoint of quality as well. Thorough inspection of forgings through centrally bored holes and with the aid of X-ray apparatus and magnetic devices have assisted in detecting flaws. For low temperature service, as for instance in turbo-generators, it has been found that rotors built up of plates [11] and held together by through bolts have been highly successful in circumventing these difficulties.

Spindles built of two or more pieces are joined by pressed fits and studs. Under the action of inertia forces the pressure between adjacent surfaces of a fit is reduced; frequently on large diameter spindles to such a point that slight differences in temperature between the parts may transfer the load from the fit to the bolts. At times, this readjustment is accompanied by changes in the center of gravity sufficient to produce vibrations. Joints at the high temperature end have also been aggravated by creep under conditions of relaxation. In an effort to relieve this impasse, the most recent designs have been built of one forging to carry the high and intermediate pressure blading directly, tapering to a smaller diameter at the exhaust end where discs are keyed and fitted to carry the large low pressure blades. Even with this improvement difficulty may arise unless sufficient fit pressure remains at operating speed to compensate for changes in temperature between the rapidly heated thin discs and the massive spindle forgings. Transient load changes that produce increased exhaust temperatures are especially undesirable.*

* A problem of importance, but which will not be discussed here, may arise in starting unless the turbine is allowed sufficient time to change temperature gradually. The admission of starting steam warms the exhaust end to a higher temperature than it would normally have when the condenser is in full operation. When the machine is brought to speed under normal vacuum the discs may decrease in temperature more rapidly than the spindle. The relative expansion

The joint consists of an outer shell, Fig. 19, subject to an external blade load p_3 lb./in.^{2} and an internal fit pressure p_1 lb./in.^{2}, forced over an internal piece subject at its periphery to the same load p_1 lb./in.^{2}. The expressions for the stresses σ_r and σ_t and the radial deflection u may be found from the well known relation,

FIG. 19.



Pressed fit on a turbine spindle.

$$\frac{d^2u}{dr^2} + \frac{1}{r}\frac{du}{dr} - \frac{u}{r^2} + (1 - \nu^2)\frac{\partial\omega^2}{gE}r = 0$$

for the specific boundary conditions. The fit pressure is determined from the condition of continuity, namely

$$u_{1b} - u_{2b} = \Delta,$$

manifests itself by increasing the bore stress even to the extent that it may exceed the yield stress. When the temperatures have again readjusted themselves the plastic strain that occurred under the transient condition and at the expense of the elastic strain will loosen the joint. Fortunately the seriousness of this problem can be reduced by thoughtful design.

where u_1 and u_2 represent the radial extensions of the external and the internal pieces respectively, and $\Delta = b_1 - b_2$ the initial radial difference at the fit. The thermal strain $\alpha\theta r$ is added directly to the equations for radial extension (this is equivalent to assuming a uniform temperature distribution in each part) with the result that *

$$u_1 = \frac{1-\nu}{E}\frac{b^2p_2 + a^2p_3}{a^2-b^2}r + \frac{1+\nu}{E}\frac{b^2a^2}{r}\frac{p_1+p_3}{a^2-b^2} - \frac{Nr^3}{8} + \frac{3+\nu}{8r}N\left\{\frac{r^2(a^2+b^2)}{1+\nu} + \frac{b^2a^2}{1-\nu}\right\} + \alpha\theta_1 r, \quad (13a)$$

$$u_2 = \frac{3+\nu}{8}\frac{1}{r}N\left\{r^2\frac{c^2+b^2}{1+\nu} + \frac{c^2b^2}{1-\nu}\right\} - \frac{Nr^3}{8} + \alpha\theta_2 r - \frac{b^2}{E}\frac{p_1}{b^2-c^2}\frac{1}{r}\{(1-\nu)r^2 + (1+\nu)c^2\}, \quad (13b)$$

where $N = (1-\nu^2)\gamma\omega^2/gE$. Neglecting the inner radius c, the fit pressure becomes,

$$p_1 = \left\{\frac{E\delta}{2a^2} - \frac{\omega^2}{g}(\rho+\xi) - \frac{E\alpha(\theta_1-\theta_2)}{2a^2}\right\}(a^2-b^2). \quad (14)$$

where $\rho = \dfrac{\gamma(3+\nu)}{8}$ and $\xi = \dfrac{p_3 g}{\omega^2(a^2-b^2)}$ and $\delta = \dfrac{\Delta}{b}$.

In this equation particularly important is the expression within the brackets since it is the criterion of fit efficiency. Thus when the speed has increased to the point that

$$\frac{E\delta}{2a^2} - \frac{\omega^2}{g}(\rho+\xi) - \frac{\alpha(\theta_1-\theta_2)}{2a^2} = 0$$

the fit pressure is completely relieved and the parts are held by the keys or the bolts. Of significance is the fact that the pressure is independent of all the spindle dimensions except the external radius and the fit allowance. Neglecting the blade load, which varies with the different machines, and

* In this analysis there has been no effort made to include the effect of disc profile; instead the disc has been considered as a uniform section. On profiled discs the inertia forces are smaller; consequently the reduction in pressure with speed is less.

assuming equal temperatures, the maximum speed at which the joint will remain tight depends on a and on δ, so that

$$\omega = \frac{1}{a}\sqrt{\frac{E\gamma g}{2\rho}}. \tag{14}$$

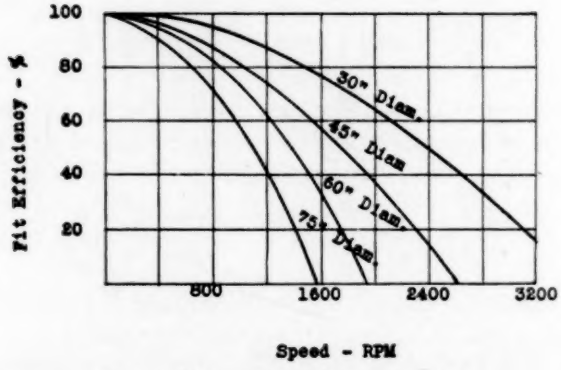
For the usual fit allowance of 0.00075 inches per inch of diameter, 63 inches is the maximum diameter for a 1,500 r.p.m. machine and 53 inches is the limit at 1,800 r.p.m. if the joint is to be effective. These values are based on the possibility of a 20 per cent. overspeed occurring during governor adjustment, or on test.

The fit efficiency represents the ratio of fit pressure under dynamic conditions as compared to the static conditions. With the same assumptions regarding blade load and temperature as employed above, the efficiency is

$$\eta = \frac{p_\omega}{p_0} = 1 - \frac{2\rho\omega^2 a^2}{gE\delta}. \tag{15}$$

In Fig. 20 the fit efficiency as a function of speed is shown.

FIG. 20.



Variation of pressed fit efficiency with speed.

Since the load is normally borne by the friction of the surfaces, it is evident that the pressure need not be completely relieved before transition occurs. It would appear from past experience that with an efficiency of less than 20–25 per cent., operating difficulties may ensue.

Any difference in temperature between the outer and inner parts lessens the pressure of the fit. When the fit efficiency has been reduced as a result of inertia forces as well, the temperature difference to produce a critical condition is well within the realm of possibility.

TABLE III.

Temperature Difference to Produce 20 Per Cent. Fit Efficiency with a Fit Allowance o. 0.00075 in./in.

	1,800 r.p.m.					1,500 r.p.m.				
Spindle Diam.	40″	45″	50″	55″	60″	40″	45″	50″	55″	60″
Temp. Diff.	49°	39°	30°	17°	2°	61°	53°	46°	38°	28°

The key to the solution of the problem of pressed fits lies in the proper choice of fit allowance. By increasing the allowance, the seriousness of the problem can be relieved without in any way impairing the joint. The maximum combined tensile stress at the bore of the outer piece is found from the usual elastic equations to be

$$\sigma = \sigma_{tb} - \sigma_{rb} = \frac{\gamma\omega^2}{4g} b^2(1 - \nu) + E\delta. \qquad (16a)$$

Under certain conditions (see footnote on page 599) during starting, the bore stresses may be increased by the temperature difference between the inner and outer parts as a result of rapid cooling of the discs. The yield stress should not be exceeded even at overspeed. Assuming failure in accordance with the maximum shear theory, the fit allowance is then defined by

$$\delta^* = \frac{\sigma_y}{E} - \frac{\gamma\omega^2 b^2}{4gE}(1 - \nu) - \alpha\theta^*, \qquad (16b)$$

where θ^* is the maximum temperature by which the forging will exceed the disc temperature and ω is the angular velocity at 20 per cent. overspeed. Good design prescribes that δ be somewhat less than δ^*.

PROBLEMS OF THERMAL STRESS.

1. Stresses in Turbine Spindles.

Internal stresses resulting from transient temperature fields that occur on starting or stopping a large rotor have been the subject of much conjecture. The stresses can be ascertained from a fairly logical analysis of the equations that prescribe elastic equilibrium after the strains are known, but the magnitude of the heat transfer coefficients, and consequently the temperature distribution [12, 13, 14] is questionable.

Thermal stresses are large where there are massive sections that require some time to rise in temperature. Exhaust end discs seldom prove dangerous since their ratio of surface area to volume is so great that rapid heating and good temperature distribution results. More dangerous is the tendency that discs exhibit toward loosening during rapid temperature changes. Size in itself does not enhance the stress, but it does introduce temperature differences that are the controlling influence.

The transient temperature distribution within a turbine spindle can be treated on the basis of the classical theory of heat conduction. Consider a solid cylinder of uniform temperature, surrounded suddenly by steam at a temperature less than the spindle temperature by the value θ^*. Heat will flow from the surface in accordance with the relation,

$$\frac{d\theta}{dt} = \lambda 2\pi a \theta_s,$$

where θ_s is the instantaneous surface temperature in excess of the steam temperature and a the outer radius in feet. Within the body the heat flows from the center outward by conduction. The continuity equation is then

$$\frac{d\theta}{\partial t} = \frac{\kappa}{c\gamma}\left(\frac{1}{r}\frac{\partial\theta}{\partial r} + \frac{\partial^2\theta}{\partial r^2}\right). \tag{17}$$

The solution to (17) for the boundary conditions

$$t = 0 \qquad \theta = \theta^* \qquad \text{for all values of } r,$$

$$r = a \qquad \frac{d\theta}{dr} + \frac{\lambda}{\kappa}\theta = 0 \qquad \text{for all values of } t,$$

is of the form

$$\theta = \varphi(t) \cdot \psi(r) \tag{17a}$$

Upon the substitution of (17*a*) the original equation reduces to the well known Bessell's form, and the solution becomes,

$$\frac{\theta}{\theta^*} = \sum_{n=1}^{n=\infty} 2 \cdot \frac{1}{\alpha_n} \cdot \frac{J_1(\alpha_n)}{J_0^2(\alpha_n) + J_1^2(\alpha_n)} \cdot J_1\left(\alpha_n \frac{r}{a}\right) \cdot e^{-\alpha_n^2 \kappa / c\gamma \, t/a^2} \tag{18}$$

$$= F\left(\frac{\kappa}{c\gamma}\frac{t}{a^2}, \quad \frac{\lambda a}{\kappa}, \quad \frac{r}{a}\right), \tag{18a}$$

in which α_n represents the nth of an infinite number of solutions to

$$\frac{\lambda a}{\kappa} J_0(\alpha_n) = \alpha_n J_1(\alpha_n).$$

The terms J_0 and J_1 are Bessell's functions of the first kind, zero and first order. Replacing θ^* by $-\theta^*$ the equation (18*a*) gives the transient temperatures on heating. The treatment of (18*a*) is not difficult with the aid of proper tables for the functions, and the literature [13] is replete with cooling and heating curves in accordance with the above expression.

The surface heat transfer coefficient varies with the fluid velocity past the surfaces and the character of the flow, particularly the turbulence and the boundary layer thickness. At slow turbine speeds it may be as low as 6 $\frac{\text{B.t.u.}}{\text{ft.}^2 \text{ hr. } ^\circ\text{F.}}$, but at higher speeds 70–80 $\frac{\text{B.t.u.}}{\text{ft.}^2 \text{ hr. } ^\circ\text{F.}}$.

Large turbine spindles rise slowly in temperature as evidenced in the comparison made in Table IV for a 22 in. and a

TABLE IV.

Temperature Distribution on Heating a Spindle Initially at 150° F. to 850° F.

$$\lambda = 70 \frac{\text{B.t.u}}{\text{ft.}^2 \, ^\circ \text{F. hr.}}.$$

		¼ hr.	½ hr.	1 hr.	1½ hr.
22 in. Diam. Spindle.....	θ_s—° F.	563°	654°	752°	801°
	θ_m—° F.	395°	535°	683°	760°
	θ_0—° F.	220°	395°	620°	731°
50 in. Diam. Spindle.....	θ_s—° F.	550°	612°	690°	731°
	θ_m—° F.	262°	339°	444°	528°
	θ_0—° F.	150°	164°	206°	311°

50 in. diameter spindle for 850° F. operating conditions.

The thermal stresses in an infinitely long cylinder,* with a bore that is small compared to the outer radius, are found from a straightforward application of the elasticity equations. The unit strains

$$\left.\begin{aligned}\epsilon_r &= \frac{\sigma_r}{E} - \nu\frac{\sigma_t}{E} - \nu\frac{\sigma_z}{E} + \alpha\theta,\\ \epsilon_t &= \frac{\sigma_t}{E} - \nu\frac{\sigma_z}{E} - \nu\frac{\sigma_r}{E} + \alpha\theta,\\ \epsilon_z &= \frac{\sigma_z}{E} - \nu\frac{\sigma_r}{E} - \nu\frac{\sigma_t}{E} + \alpha\theta\end{aligned}\right\} \qquad (19a)$$

together with the compatibility relation between ϵ_t and ϵ_r

$$\frac{d(r\epsilon_t)}{dr} - \epsilon_r = 0 \qquad (19b)$$

and the equilibrium expression

$$\frac{d(r\sigma_r)}{dr} - \sigma_t \qquad (19c)$$

define a unique condition. Without elaborating on a solution to the final equation for the particular boundary conditions in view of its simplicity, suffice to say that the thermal stresses at the bore ($r = 0$) on cooling are,

$$\sigma_r = 0 \qquad \sigma_t = \sigma_z = \frac{E\alpha\theta^*}{1-\nu}\left(\frac{\theta_m}{\theta^*} - \frac{\theta_0}{\theta^*}\right) \qquad (20a)$$

and at the surface $r = a$,

$$\sigma_r = 0 \qquad \sigma_t = \sigma_z = \frac{E\alpha\theta^*}{1-\nu}\left(\frac{\theta_m}{\theta^*} - \frac{\theta_s}{\theta^*}\right), \qquad (20b)$$

where θ_m is the mean temperature, θ_0 the temperature at the bore, and θ_s the temperature at the surface. In Table V

* Imposing the restriction that the length of the cylinder is great compared to the radius justifies the assumption that cross sectional planes of the cylinder remain plane even after the temperature field is imposed, or more briefly $\epsilon_z = \epsilon_0$ = Constant.

TABLE V.

Maximum Thermal Stresses of Heating a Spindle Initially at 150° F. to 850° F.

	22 in. Diameter.	50 in. Diameter.
Max. bore stresses	+63,600 lb./in.²	+45,500 lb./in.²
Max. surface stresses	−72,600 lb./in.²	−54,500 lb./in.²

the maximum thermal stresses have been calculated from the transient distribution in Table IV. For the 22 in diameter spindle, both the maximum bore stress and the maximum surface stress occur in the first twenty minutes of operation, whereas for the larger spindle the surface stresses peak at 1/2 hour, but the maximum bore stresses occur only after an hour's operation.

To the thermal stresses must be added the inertia stresses from rotation, with the result that on starting from cold the stresses undoubtedly exceed the plastic limit. This condition is not serious in the spindle proper for the residual forces that result can only produce a more favorable stress distribution during cycles less severe.

More far reaching in effect are high thermal stresses in the blade roots, since any plastic yield will loosen the blades when the steady state is again realized. Undoubtedly the stresses are higher than the tabulated values given above, inasmuch as the blades heat rapidly.

A thermal problem of a similar nature may occur during unintentional body or shaft rubs at points of minimum clearance. These rubs arise during the starting cycle or under sudden load changes, and are generally attributed to bent spindles. The localized rubbing on the high side of the spindle generates heat so rapidly that there is a rise in temperature in the material immediate to the contact point. The thermal expansion is restrained by the surrounding material, resulting in a stress of

$$\sigma = -\frac{E\alpha\theta}{1-\nu}$$

and added distortion of the spindle toward the high side. This additional spindle deflection merely increases the rubbing with the result that the whole process is cumulative.

The restrained thermal expansions are objectionable since the local temperature rise is usually sufficient to produce

compressive stresses in excess of the yield point, with corresponding plastic flow. When a stress of 25,000 lb./in.^{2} may be produced during a rise of only 100° F. the exacting nature of the problem is appreciated. After the rub is relieved and the spindle returns to a steady state, conditions of equilibrium demand that the spindle be deflected on the side opposite the rubbed portion as a result of the residual stresses. The resulting eccentricity does not have to be great to cause severe vibration and other operating difficulties.

On older machines spindle distortion from gland or dummy rubs is not at all uncommon; in fact the majority of turbine outages have been caused by body rubs and blade repairs. The newest designs have partly circumvented the problem by building thin sleeves over the shaft at points of reduced clearance. Rubbing on the sleeve will distort the sleeve but not the spindle. Notwithstanding the modern improvements, however, the problem is important, and operating engineers make every effort to insure freedom from rubs during the starting period.

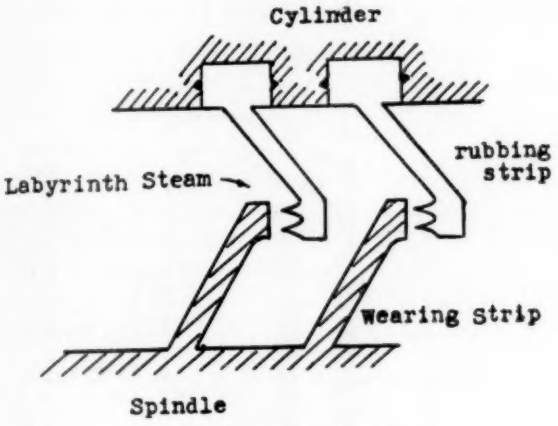
2. Stresses in Dummy and Gland Strips.

Not all the problems incident to starting or stopping of turbines and involving stresses in excess of the plastic limit may be treated with the lack of concern that is generally associated with spindle stresses produced by transient temperature fields. The deleterious effect of body rubs, which produce a localized plastic flow resulting in a permanent spindle distortion, have already been mentioned; still another example is apparent from the behavior of "self-relieving" gland strips.

The thrust on a reaction turbine created by the drop in pressure between the inlet and exhaust is balanced by a series of dummy pistons attached to the high pressure end, and exposed on one side to steam at full inlet pressure and on the other to exhaust pressure. In the interest of maximum efficiency, the least possible steam leakage across the dummy piston is secured by labyrinth seals consisting of thin metal strips fitted across the dummy piston surfaces. The strips are arranged so that as steam expands by a series of throttlings from the high to low pressure regions, it will follow such an undulating path that the kinetic energy will be lost after

each expansion. The advent of axial clearance blading has brought the axial clearance dummy strip with its wearing surface on the side; and both blades and dummy strips are ground to uniform clearance in the same operation. Integral with the spindle is machined the rubbing strip, Fig. 21, while

FIG. 21.



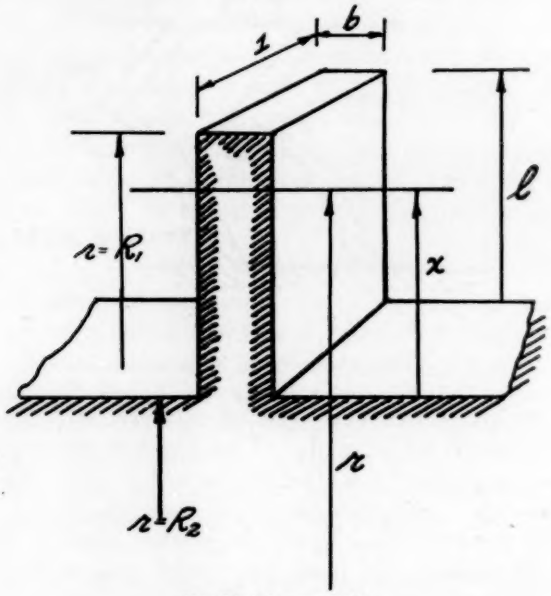
Conical "self-relieving" dummy strip.

the wearing strip is driven in short sections into the cylinder and held in place by tongues. The distinct advantage of the design was supposed to rest in the fact that after the machine was in service, any accidental rubs on the dummy strips heated the conical wearing piece on the spindle, which was constrained to move in both the radial and axial directions under the temperature strains. The net result was that the axial movement in seeking an equilibrium position relieved the two parts from contact.

On analysis the problem appears more insidious, however, for the thin wearing strips may be at a considerably higher temperature than the spindle body proper, especially during grinding or on bringing the machine on the line. The resulting stresses, usually in excess of the yield point, will cause the strip to move backward in relieving the strains, and into a position it will retain permanently. The corresponding increase in leakage will modify the efficiency.

The problem in its essential features, shown in Fig. 22, may be represented by a thin radial strip projecting from a body of infinite mass into a rapidly moving fluid having a temperature different from that of the spindle mass by θ^*. In reality the temperature field is a function of time, but since the perimeter is large as compared to its volume, the temperature may be assumed to be produced almost instantly. In comparison to the rate of change of temperature within the

FIG. 22.



Simplified dummy strip.

spindle this approximation is satisfactory. The temperature distribution in a linear strip under steady state conditions with gain of heat through the surface is represented by,

$$\frac{d^2\theta}{dx^2} - B^2\theta = 0,$$

where $B^2 = 2\lambda/\kappa b$. For the boundary conditions

$$x = 0, \qquad \theta = \theta^*,$$

$$x = l, \qquad \frac{d\theta}{dx} + \frac{\lambda}{\kappa}\theta = 0$$

the temperature distribution is

$$\theta = \theta^* \frac{\sinh\left(\operatorname{cotanh}^{-1}\dfrac{B\sinh Bl + \dfrac{\lambda}{\kappa}\cosh Bl}{B\cosh Bl + \dfrac{\lambda}{\kappa}\sinh Bl} - Bx\right)}{B\cosh Bl + \dfrac{\lambda}{\kappa}\sinh Bl}, \qquad (21a)$$

Since l is small, (20a) may be approximated by

$$\theta \leqq \theta^*\left(1 + \frac{B^2(R_1 - r)^2}{2}\right). \qquad (21b)$$

The radial and tangential stresses within the strip are determined from the elastic equations of equilibrium for a thin disc, with an additional term representing the thermal strain

$$\sigma_t = \frac{E}{1-\nu^2}\left(\frac{u}{r} + \nu\frac{du}{dr}\right) - \frac{E\alpha\theta}{1-\nu},$$
$$\sigma_r = \frac{E}{1-\nu^2}\left(\frac{du}{dr} + \nu\frac{u}{r}\right) - \frac{E\alpha\theta}{1-\nu}.$$

The boundary conditions are:

$$u = 0, \qquad r = R_2,$$
$$\sigma_r = 0, \qquad r = R_1.$$

Introducing (21b) and simplifying, the tangential stress * is

$$\sigma_t \leqq -\frac{E\alpha\theta^*}{2\cosh Bl}\left\{\frac{R_2^2}{r^2}\left(1 + R_2^2\rho^4\frac{B^2}{12}\right) + B^2\left(l^2 - \frac{R_2^2\rho^4}{12}\right) + 1\right\}, \qquad (22a)$$

where $\rho^2 = R_1^2/R_2^2$. Since $r \leqq R_2 \leqq R_1$ and l is small, equation (22a) may be approximated by

$$\sigma_t \leqq -\frac{E\alpha\theta^*}{\cosh Bl}\left(1 + \frac{B^2l^2}{2}\right) \leqq -E\alpha\theta^*. \qquad (22b)$$

This stress is nearly constant throughout the length of the piece.

* The radial stress is negligible.

On starting the turbine, the labyrinth strips rise rapidly to the temperature of the surrounding steam while the spindle because of its size takes considerably longer. Under these conditions temperature differences as great as 300° F. may exist between the outer edge of the gland strip and the spindle body. The resulting tangential stress in the strip on a machine for 850° F. service is about 53,000 lb./in.^{2}. During transient conditions, in an effort to grind to a uniform axial clearance, or during unintentional rubs, the stress is even greater.

Sudden high stresses are not harmful when the strip is radial, nor even on conical strips providing the yield point is not exceeded, but on conical strips where the stress exceeds the plastic limit, the strip relieves itself by plastic flow in an axial direction at the expense of leakage area and efficiency.

The problem is vexing for no amount of grinding can possibly bring the clearances smaller unless it is undertaken so carefully that serious temperature differences are eliminated; in fact continued grinding will generally aggravate the condition. In view of this analysis it is apparent that the stress distribution in a conical "self-relieving" gland militates against its continued use.

NOTATIONS.

σ = Normal stress, lb./in.^{2}
τ = Shearing stress, lb./in.^{2},
ϵ_e = Elastic strain, in./in.,
ϵ_p = Plastic strain, in./in.,
E = Modulus of elasticity, lb./in.^{2},
ν = Poisson's ratio,
γ = Specific weight of material, lb./in.^{3},
ω = Angular velocity, radians per second,
g = Gravity constant,
θ = Temperature, ° F.
λ = Coefficient or surface heat transfer, $\frac{\text{B.t.u.}}{\text{ft.}^2 \text{ hr. } ^\circ \text{F.}}$,
κ = Conductivity coefficient, $\frac{\text{B.t.u. ft.}}{\text{ft.}^2 \text{ hr. } ^\circ \text{F.}}$,
c = Specific heat, $\frac{\text{B.t.u.}}{\text{lb. } ^\circ \text{F.}}$,
α = Temperature coefficient of elongation, in./in. ° F.,
r = Radius, in.,
t = Time,
u = Radial extension = $r\epsilon_r$, in.,
a = External radius, in.

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A New Application of the Ritex Process to the Manufacture of Chrome Brick.—R. P. HEUER (*Steel*, Vol. 97, No. 8.) The Ritex process for the manufacture of unburned magnesite brick was announced in 1931. It was characterized by a proper grinding, grading and blending of the magnesite particles, the use of high forming pressures up to 10,000 lbs. per sq. in. for moulding, and the use of a refractory bonding agent in the brick mix to permit the use of the brick without kiln firing. The brick produced were found to have many advantages, particularly an improved resistance to spalling. As a result the production and use of the Ritex magnesite brick grew until at present they are the most widely used. To manufacture brick from chrome ore, however, numerous changes in equipment were necessary. It was found necessary to equip the brick forming presses with de-airing equipment to evacuate the air from the brick mould just before the high forming pressure was applied. After this and other adjustments were made a complete series of tests compared the new Ritex brick with chrome brick of regular manufacture. The results, illustrated in a series of curves, show how the less desirable burned brick starts to deform at moderate temperature and fails by shearing whilst the Ritex brick continues to expand against the applied load to the highest temperature of test. Other favorable test results shown by Ritex chrome brick including crushing strength, refractoriness under static load and volume stability on a high temperature reheat test. In the entire development resistance to spalling was paramount. Chemical analysis shows a high percentage of magnesia in the Ritex chrome brick which produces particular advantages. The successful use of these brick commercially is indicated by the fact that in less than one year they have found their way into regular use in a majority of the important open hearth shops in this country. For many other types of furnaces the new refractory may be advantageously employed.

R. H. O.

THE RELATION OF POWER TO ANTI-KNOCK FUEL REQUIREMENTS FOR MULTI-CYLINDER ENGINES.*

BY

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I. PRIMARY CONSIDERATIONS.

There is no problem more fundamental in the study of automotive engine performance than the determination of the minimum fuel quality required for satisfactory operation. Into the satisfactory solution of this problem enters the study of every factor governing the attainment of optimum power, economy and life. Yet, important and revealing as this study is, it is the phase of automotive engine operation upon which the smallest amount of accurate data is available. There are many reasons for this. First, the experimental difficulties are enormous because of the many factors which have to be controlled. Secondly, the problem is as yet of no great importance in the case of automobile engines which make up the great bulk of automotive engines; hence, the automobile engine manufacturers have not concerned themselves with it. Thirdly, in that field of operation where the problem is of very great importance, namely aviation, the few manufacturers of large engines have neither the means nor the equipment to go into any extensive and wholesale study of it on any make of engines other than their own. The work is thus left for the Federal Government Laboratories or those of the various oil companies. The latter, however, have confined themselves mainly to single cylinder studies of the anti-knock quality of their products. Consequently, the bulk of whatever data we have on the subject under discussion has been gathered in the various Government laboratories.

* All statements contained herein are the private opinions of the writer and are not to be considered as official or reflecting the views of the Navy Department. —SANDOR D. RUBENZ, July 1932.

It should be emphatically understood at the outset that the only satisfactory solution to this problem for any given engine is an experimental one. Moreover, it will be seen that the problem may require many different solutions for the same engine. From the present state of our data it is impossible to predict by any rational means with any accuracy the detonating tendencies and consequently, the anti-knock requirements of an engine under varying circumstances. The reasons, which will be more elaborately discussed later in this article, lie in our inability to understand how a group of uncontrollable variables affect the performance of the engine. Take as an example the atmospheric temperature. A change in this factor will certainly change the power output and the anti-knock requirement. But how? Will the change in each be in the same direction or in opposite ways? Is there any relation between the rates of change? How will corrective measures as applied to one affect the other? There are no data which will answer these questions and others like them. Nor is it believed that there can be from the very nature of the problem which involves a host of variables no one of which can be isolated from the others.

For this reason, I propose to consider first the experimental methods available for the solving of such questions. Later, I will consider some available data to see if we can arrive at some means of prediction and control over the problem.

In an earlier paper [1],* I considered in a general way the testing of fuels for their anti-knock value. In that paper were discussed the basic qualifications which governed the selection of a method of test. It was pointed out, for instance, that a single cylinder liquid-cooled engine which lends itself readily to methods admitting the recognition of the initiation of knock and whose cylinder walls could be kept at a constant temperature was the only instrument available for reliable work along that line. It was pointed out also that the measurements of power or temperature differences as indices to knock rating were not accurate enough to be of value and that the most reliable index was the compression pressure at which

* These numbers refer to references cited at end of article.

knock started, which could be most easily identified, for instance, by the initiation of the audible "ping." When we come, however, to consider the selection of a method by which we may determine the required anti-knock value for a practical multi-cylinder engine, we come upon an entirely new phase of the problem. The end of both investigations is the same: to find the best possible combination of engine and fuel. One phase seeks to solve the question: what is the usefulness of this fuel and how shall it be improved or maintained? The other answers the question: what is the minimum fuel value for this specific engine?

The considerations governing the choice of a method of test are basically the same in each, but they cannot be employed so usefully in the multi-cylinder engine. Therefore, they are often ignored. For instance, the compression pressure at the initiation of knock cannot be determined in the large engine because no instruments are available for the purpose. The human ear which is so useful in the case of the single-cylinder is inoperative here because of the terrific noise. Then, too, the air-cooled cylinder which is used on most present day aircraft engines cannot be maintained at a constant or predetermined temperature. It is utterly beyond control of the operator and depends upon such variable things as atmospheric temperature and barometer. Another disturbing factor found in multi-cylinder engines, especially in those without rotary inductors, is uneven distribution of the fuel mixture to the different cylinders. It was pointed out in the earlier article [1] how this would give misleading results in testing fuels because mixture ratio plays an important part in determining the knocking tendency of a fuel. This factor, however, is not a fault in the present case; actually it is a blessing, for if uneven distribution results in detonation in one cylinder before it occurs in any of the others, that cylinder is a potential danger point; it is well to find it out and to provide a fuel capable of resisting the conditions set up in that cylinder.

II. A STUDY OF AVAILABLE METHODS.

We have seen that fortunately for accurate fuel testing, no reliance need be placed upon either power output or temperature rise as a sign of knocking in the single-cylinder engine.

In the multi-cylinder engine, however, these are the only possibilities open for use. The power output is very rarely used. It is well known that detonation has no immediately perceptible effect upon power until it is present in considerable intensity. While it may not be dangerous to run an engine with slight or even moderate knocking, it is always a possible source of danger. It represents a gradual accumulation of heat, which is not dissipated as rapidly as it normally would be, and in time will result in pre-ignition, piston seizure, plug burning, valve warping and other dangerous conditions. Consequently, whenever possible, the required fuel determination should be made for the initiation of knock. From this standpoint, the temperature method is superior to the power output method, and it is used universally in one form or another in multi-cylinder engine fuel tests.

The basis of the temperature method is the phenomenon, discovered by Midgely and McCarty, that a detonating fuel causes abnormal radiation losses to the cylinder walls. In an engine running with constant operating conditions, as would be the case with an airplane engine cruising in the air, the heat input to the cylinder and, therefore, the maximum temperatures of the cylinders would be constant, provided always there was no knocking or pre-ignition. The constant operating conditions would be:

1. Crank-shaft speed, which governs the number of heat input cycles per unit time.
2. Throttle opening, which is a function of the speed, and governs the charge weight per cycle.
3. Ignition timing, governing the time-position of maximum pressures and temperatures.
4. Weight-ratio of fuel to air (or mixture strength) which governs the heat input value of the charge, the length of time the flame is in contact with the cylinder walls and the maximum pressure for a given charge weight in the cylinder.
5. Speed of the plane in the case of air-cooled engines, which controls the heat-dissipative rate of the cylinders to the cooling medium.
6. Altitude level of flight, which determines the air-charge density at intake to the carburetor and, therefore, the

maximum pressures for a given heat input in the fuel charge.

7. Oil temperature, which governs the heat transfer rate from piston to cylinder walls.

These conditions are under control of the operator and thus subject to the demands of fuel economy, power requirements, plane speed, etc. Some factors which are not controllable, but which affect cylinder temperatures, are atmospheric barometer changes at any given altitude and atmospheric temperature and humidity. Granting, then, the maintenance of a cooling air blast and a flow of oil under the proper pressure, an engine with such a constant load and unchanging operating conditions would run for a long time without any change in the cylinder temperatures. The onset of detonation, however, for any reason whatever, will result in an increase in these temperatures. Hence, if methods of temperature measurement sufficiently sensitive are at hand, they can be used to determine the fuel requirement of the engine.

The particular method used depends sometimes upon the viewpoint of the investigator and more often upon the type of engine. Obviously, a different type of test is required for a water-cooled engine than for a vapor-cooled or an air-cooled engine. Just where to measure the temperature is the problem. In the liquid-cooled engine that problem is simplified, since the only places available for temperature measurement are at the jacket inlet and outlet. It is useless to try to find the temperature of the cylinder walls, because except for the almost infinitesimally thin inner surface, the wall metal is practically at the temperature of the liquid. In vapor- and air-cooled engines we find the problem somewhat more complicated. We cannot measure the temperature of the cooling medium; hence, it is the cylinder temperature that must be sought.

The most usual place is somewhere on the cylinder head. The easiest place is on the spark-plug boss or beneath the plug gasket. Thermocouples imbedded in the gasket will hold together more substantially than those in the boss, but they present the difficulty that the temperatures they record are in large measure dependent upon the spark-plug used.

For the same quantity of heat input to the cylinder head, the thermocouple in the gasket of a "hot-running plug" will read considerably higher than that of a "cold-running plug." Since it is usual practice now to limit air-cooled engine cylinders to a temperature of about 525° F., it will be seen that gasket temperatures may give misleading conclusions. With a cold-running plug the cylinder head may easily be running dangerously hot by the time a gasket temperature of 525° F. is reached. To a lesser extent the boss temperatures are similarly affected by the plug.

This naturally leads to the conclusion that the thermocouple should be located in the center of the head, because head temperatures should be independent of the spark-plug condition, varying only with the rate of heat input. However, because of the finned construction of the cylinder heads, and the consequent narrow spaces available for tapping into the head wall, it is usually very difficult to make substantial thermocouple connections. Unless these connections are firmly imbedded they will soon vibrate loose from their contacts and give erratic and misleading readings. In this respect the gasket thermocouple connection may be made very strong since it is easily accessible and virtually immune from the effects of vibration. All things considered, however, it makes little difference where the temperature is measured. For the purposes of this test, it is the relative temperature rise from one fuel to the next which is important. Later we shall see that the temperature rises similarly whether measured in the head, spark-plug boss or gasket. For the purposes of this article, all these temperatures are called "head" temperatures.

A very important temperature which must be closely controlled in air-cooled engine cylinders is that of the flange—the cylinder base through which it is bolted to the crankcase. This temperature is considered a direct index to piston friction, and if carefully watched, will reveal any tendency toward piston seizure in the cylinder. The excessive temperatures and heat input resulting from continued detonation cause undue expansion of the piston. This leads to increased piston friction, which is clearly indicated by a rise in the flange temperature. The thermocouple is placed somewhere be-

tween the thrust side of the piston and the rear of the cylinder, giving a combination of the greatest wall pressure and maximum cylinder barrel temperature. This whole question of cylinder temperatures is very important to good operation and will be considered in more detail in another article.

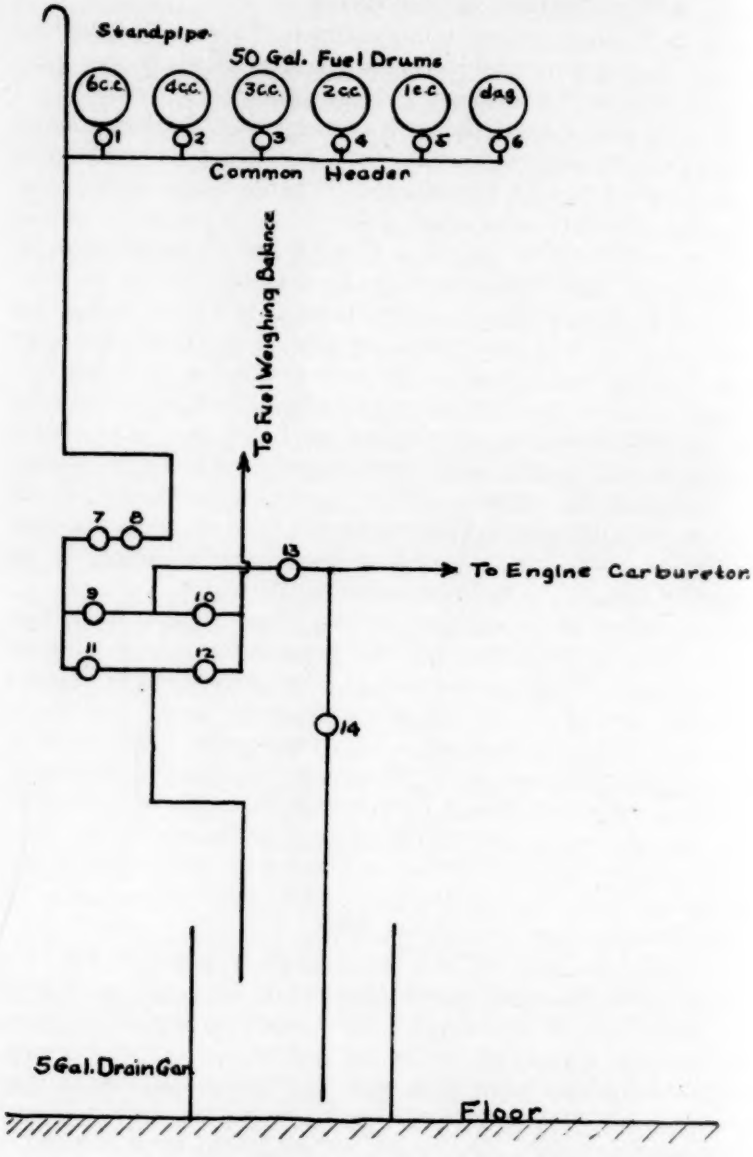
Having now considered in a cursory way the best places for temperature measurement, the next point to consider is the method of test or the method of temperature interpretation. In all cases, the chief point is to duplicate a set of running conditions as nearly as possible for all the fuels to be tried. Some one condition is to be selected as the control. Any change in this control is then interpreted as an indication of detonation. As we have already seen, some form of temperature measurement is the best control so far used.

In air-cooled engines the cylinder head temperature is the only control available. It may be used in several ways: with the engine developing maximum power at a constant speed, or, with varying speeds, over a range of fuels of varying quality, or with power varying on a range of propeller-load speeds for each fuel. In all methods the criterion is an abnormal rise in the cylinder head temperature.

Detonation is dependent, among other things, upon two major factors: maximum cylinder pressure and maximum temperature. Both these factors themselves depend upon the same operating conditions: crank-shaft speed, initial air density (which is a function of the carburetor inlet air temperature and pressure and the amount of throttle opening), ignition timing and ratio of fuel to air in the explosive mixture. It is imperative, to get reliable comparative anti-knock data for the various fuels, that the carburetor air temperature and barometer and, if possible, the cooling air temperature, be maintained constant for all the fuels.

In order to keep as nearly constant as possible the carburetor inlet and cooling air temperatures, and barometer and humidity, all comparative fuel running should be done on the same day even if the carburetor air is conditioned. If a number of fuels are to be run, this means that the change from one to the other must be made rapidly and without stopping the engine. A convenient set-up for large engines is shown in Fig. 1. Fuels of the various Ethyl Fluid concentra-

FIG. 1.


Standpipe
50 Gal. Fuel Drums
6c.c.
4c.c.
3c.c.
2c.c.
1c.c
dag
1
2
3
4
5
6
Common Header
To Fuel Weighing Balance
7
8
13
To Engine Carbureter
9
10
11
12
14
5 Gal. Drain Can
Floor

tions are mixed up when ready to use, and stored in the fifty-gallon drums. The test is started with the highest concentration to be tried, this being chosen so as to provide an ample margin of safety on the non-knock side. For example, if it is estimated that a certain engine will require a fuel with two cubic centimeters of Ethyl Fluid per gallon, the first fuel used is one with, say, six cubic centimeters; the other drums contain the successive fuels to be used, each fuel having a decreasing amount (in the order of one cubic centimeter per gallon) of the Ethyl Fluid. The normal flow of fuels, then, is as follows: all the drums excepting the one containing the fuel being used at the moment are cut off from the header by means of their respective valves. Valves 7, 8, 9 and 13 are open, allowing clear flow to the engine carburetor, whereas 11, 12, 10 and 14 are closed. The engine is then running normally. When a power reading is desired, valve 10 is opened, filling a bottle on a torsion balance. When a known weight of fuel is in the bottle, valve 9 is closed, and the engine is now running on the bottle alone. The number of seconds it takes to empty the bottle of the known weight of fuel gives the fuel consumption. When the bottle reading is finished, valve 9 is opened, the bottle is refilled and valve 10 is again closed, awaiting the next power reading.

Suppose, then, that we are running on six cubic centimeters Ethyl Fluid. When this run is finished, it is desired to change to the fuel doped with four cubic centimeters as rapidly as possible. Normally at this time, valve 1 is open, whereas all the other valves leading from the various drums to the common header are closed. Valves 7, 8, 9 and 13 are open. The others are closed. The bottle is filled with fuel. Then valve 1 is closed to shut off the six cubic centimeters supply. In the meantime valve 11 is opened, draining the line into the drain can on the floor. When the line is almost drained, valve 9 is closed and 10 is opened to allow running on the bottle. To facilitate rapid changing, valve 12 is opened, draining the bottle into the can. Valve 14 is now opened to allow this pickup line to be primed by fuel from the carburetor while valve 13 (a needle valve for fine adjustment of the fuel pressure) is closed. The engine is now running upon fuel drained into the can from line and bottle. The five-gallon

drain can will hold sufficient fuel to keep a fairly large engine running for several minutes. When the line and bottle are completely drained, valve 2 is opened, cutting in the four-cubic centimeter Ethyl Fluid fuel. Valves 11 and 12 are closed, while 9 and 10 are opened. This allows the bottle to be filled with the new compound after which valve 10 is closed. Valve 13 is now opened and valve 14 closed, and the engine is running normally on the four-cubic centimeter fuel. The same procedure is followed when changing to any other fuel.

The large fuel supplies used here are obviously suitable only for engines of the high powers found in aircraft power plants. Such engines will use from 20 to 70 gallons of fuel per hour. The usual automobile engine will not use more than a few gallons per hour at full power. In such a case, the fifty-gallon tanks will be replaced by five- or ten-gallon cans which will hold sufficient fuel to allow continuous running throughout the test. The size of the whole set-up will be reduced accordingly.

The use of the drain can allows almost complete and immediate clearing of the engine-fuel system of one fuel before turning on the next, thus increasing the accuracy of the results. Its use is possible only with a fuel pump with an adequate pressure-relief valve in the by-pass. Otherwise the engine suction will not be sufficient to lift the gasoline from the drain can to the carburetor. In this latter case, the new fuel must be introduced before the old fuel has been entirely used up. This means a mixing of the two dope-concentrations, with the result that the engine must be run for some time until it is certain that only the new concentration is being burned. This results in a waste of time and fuel, and in many cases, false conclusions. It is clearly advantageous when an engine is not normally furnished with a fuel pump, to use one with a by-pass and a suitable relief valve, installed in the test set-up. Obviously, it cannot affect the results if the fuel pressure in the carburetor is properly maintained, and it will greatly facilitate the investigations.

As already pointed out, with an engine running under normal conditions with no detonation, and speed, throttle position, spark-timing and air-fuel ratio kept constant, no

change in temperature will occur when changing from one fuel to another. If, however, detonation just begins to appear with the use of the new fuel, there may be an increase in temperature, but this will not be immediately noticeable because of the very considerable lag in the thermometric system. For this reason, at least two readings should be taken with each fuel, each separated by, say, five minutes. That is, after the engine is running normally on the fuel just introduced, it should be allowed to run for five minutes before a reading is taken to allow all changing conditions to settle themselves. If no change in cylinder head temperature is noticed, repeat the reading five minutes later. If no rise is noticed this time either, it may be assumed that no knock is taking place. If, however, knock is occurring, the second reading will almost certainly show an increase in the cylinder temperature even if the first reading did not. Unless the knock is very light, subsequent readings will show continually increasing temperatures, since detonation is accompanied by a continual rise in maximum cylinder temperatures.

If the detonation is at all severe, great care must be exercised to prevent burning up the engine. The cylinder temperatures may rise fairly rapidly, especially if the engine is high-powered and is running at high speeds on full-load. It is good practice, therefore, to keep sharp watch upon the pyrometers when changing fuels and while running to allow conditions to settle. If the temperature rise is immediate, there is no need to run any longer than necessary to take a set of readings for record, after which the throttle should be cut immediately to allow the engine to cool.

It has already been stated that three ways of running the engine are available. I have preferred to use the constant speed-full-throttle method because it is the simplest, most economical in use of fuel and time, and in general gives the best results. Full-throttle operation imposes most severe conditions of temperature and pressure upon the engine structure and, therefore, time is a very important factor. The engine is operated at its rated speed with the carburetor mixture control set to give minimum fuel consumption at maximum power. This carburetor setting is called the best setting and simulates the most severe temperature conditions

the engine is likely to encounter when taking off at sea level or when climbing with a high load. Consequently, any fuel determined as safe at this condition is certainly safe under more normal conditions of operation when the engine is operating at reduced throttle openings or reduced air densities (as when cruising in the air) and with a mixture strength richer than best setting, which gives considerably cooler operation than the leaner mixture.

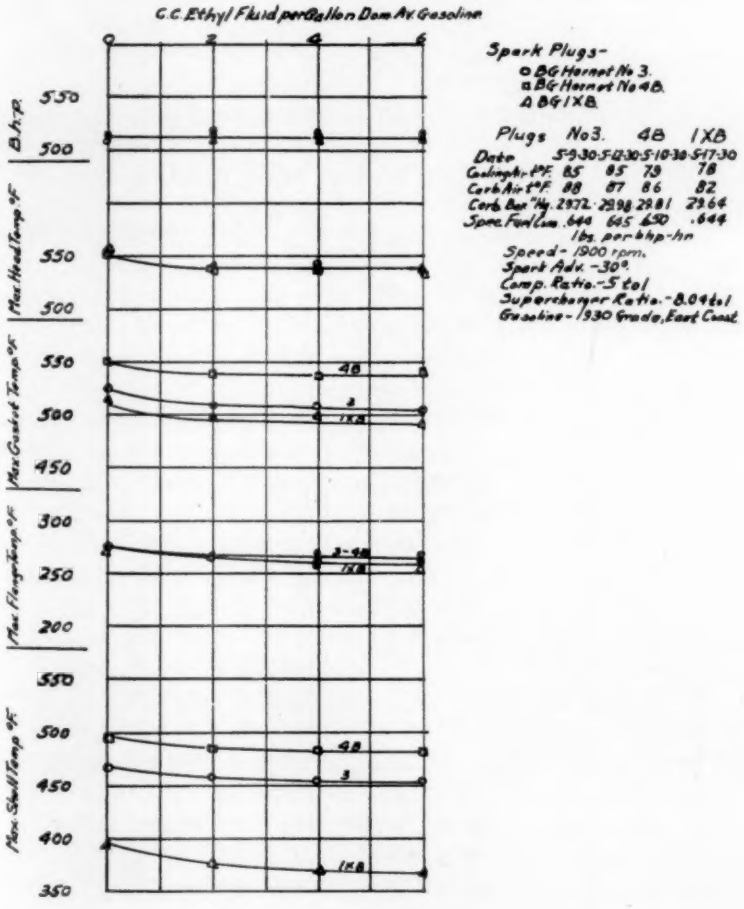
In this test, then, all conditions are kept constant, the only independent variable being the anti-knock rating of the fuel, while the dependent variable is the temperature. The results are plotted as the maximum cylinder temperature against the anti-knock rating of the corresponding fuels in cubic centimeters Ethyl Fluid per gallon of the standard base fuel, or per cent. benzol, or Heptane-Octane rating.[1] The curve will be a horizontal straight line up to a certain rating, when a sharp break upward in temperature occurs. The rating at which this break occurs is the minimum fuel requirement of the engine. Such a curve is shown in Fig. 2. This curve shows the results of a test on an engine developing 525 B.H.P. at 1900 r.p.m. It is a nine-cylinder air-cooled radial engine of 1750 cubic inches total piston displacement. It is seen that 2 cubic centimeters of Ethyl Fluid per gallon of Navy Standard East Coast Domestic Aviation Gasoline (1930 specifications) are required for safe operation. This curve also shows that wherever the cylinder temperatures are measured, they will show increases at the same anti-knock rating when detonation sets in. Therefore, it is immaterial whether the temperature is measured in the head or in the spark-plug gasket, so long as the limiting safe temperature for that part of the cylinder where the measurement is made is known and not exceeded.

It should be stated here that full-throttle operation will not always be possible. The demand for increased altitude performance of radial engines has resulted in so boosting supercharger pressures in recent designs as to give sea-level horsepowers and brake mean effective pressures far too dangerous for the strength and heat dissipative qualities of the cylinders. The trend, undoubtedly, will be to limit sea-level operation of such engines to a rated power output at

which the manifold pressure will be in the neighborhood of atmospheric or slightly higher. The fuel determination test will then be made with the throttle fixed to give this rated power at rated speed.

Since the spark-plug gasket is the most convenient place for temperature measurement, and most engines are tested with measurements at that point, Navy practice sets the temperature limit at about 525° F. as measured in the gasket. The real head temperature, as seen from Fig. 2, may be, and

FIG. 2.



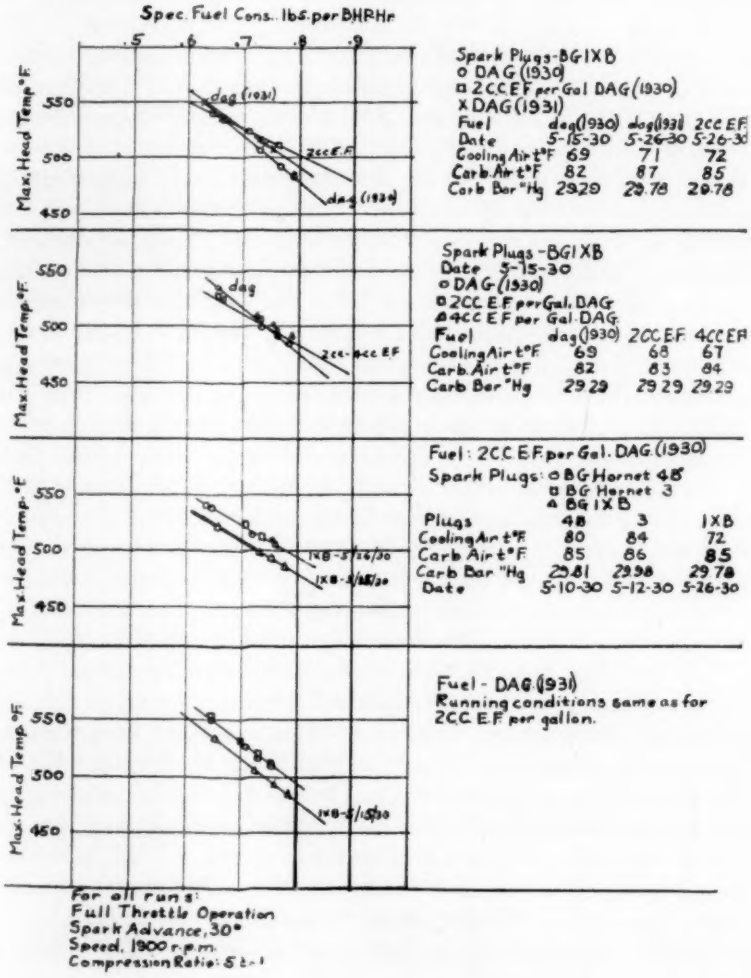
usually is, somewhat higher than the gasket temperature, depending on the plug used. It is found in service operation, however, that the average air-cooled engine will give trouble from over-heating when a gasket temperature of 525° F. is reached, irrespective, apparently, of the head temperature. Incidentally, the subject tests were run with a fuel consumption of .64 lb. per B.H.P.-hour. Any attempt to reduce this figure resulted in gasket temperatures exceeding 525° F. When it is considered that best mixture strength occurs at a consumption somewhat under .55 lb. per B.H.P.-hour, it is seen from the curve that this engine runs too hot for sea-level operation with best fuel economy at full-throttle. This is true only so far as our present limited knowledge of safe cylinder temperatures goes. Further testing may show that higher temperatures if measured in the head are thoroughly safe. The whole matter of cylinder temperatures demands considerable research before any real, reliable limits can be set.

Recent designs have resulted in cooling the cylinders of large engines so that the maximum operating temperatures can be kept below 400° F., even with increased power output, but tests made upon three such engines at one Government laboratory strongly indicate that the limiting temperatures for safe operation have been similarly lowered. For instance, an engine of 1820 cubic inches displacement will develop about 625 B.H.P. at 1900 r.p.m. with maximum cylinder head temperatures as low as 400° F., whereas a previous design of 1750 cubic inches resulted in a temperature of over 550° F. at a B.H.P. of 525. Nevertheless, the 1820 cubic inch engine developed troubles from over-heating when its head temperature exceeded 450°, whereas the earlier engine ran with comparative freedom from such troubles at temperatures of 530° and over.

A valuable supplementary test to the full power-constant speed method just outlined is to vary the mixture strength for the various fuels. With all other controls constant, a reduction in the fuel content of the charge, up to a certain ratio, causes an increase in the cylinder temperature and tends to induce detonation if this condition is incipient. This test is more severe and takes more time than the constant

fuel flow method, but it gives much valuable information about the performance of the engine. A study of the data obtained on such a test yields some highly interesting conclusions, which will be considered subsequently. The results are plotted on Fig. 3 and are for the same engine discussed previously. A careful study of these curves shows that a combination of the fuel requirement run at fixed throttle,

FIG. 3.



speed and mixture ratio and the mixture control run with the same fuels, will give much significant information upon the heating and, therefore, upon the fuel economy characteristics of an engine. This will be discussed more fully in a subsequent part of the article.

Obviously, the tests just outlined ignore the very important uncontrollable variables of atmospheric and mixture charge conditions. An engine required to develop a certain power in the tropics will have different knocking tendencies from those it will have if operating in a temperate zone. An engine will need a different anti-knock fuel when using a mixture heater or a hot-spot from what it will need when running without them. Summer imposes conditions different from winter's. If a supercharger is used, the heating characteristics of the impeller are very important. The method of installation on the plane, or of cowling, or whether the propeller is to be geared or direct-driven—all of these variables introduce differences in the conditions governing detonation. How shall we simulate the effects of such variables on the test stand? The time, the cost, to say nothing of the equipment required, impose enormous difficulties. The best answer seems to lie in a statistical study of our experience, but this has been gathered in such random fashion that up to now it is largely meaningless.

In the absence, then, of such a wide variety of tests (it is, indeed, questionable whether the variety of results will have any real value for any one engine) the constant speed tests as outlined, if run at such conditions as approximate the most severe service operating conditions, should give results which are reasonably safe. In these few considerations lie the best evidences that the problem of fuel selection is experimental and particular to each individual engine and that, in the interests of maximum safety, the best solution is one which satisfies the most severe service conditions the engine is likely to meet. The experimental work, then, may be confined to the type of tests already outlined, run at several combinations of cooling and carburetor air temperatures. This, however, forces a compromise between two very important factors: time and cost. The equipment necessary to save time in changing the air temperatures is very costly. But if cost is

important and this equipment is lacking, it is necessary to test the engine over a period of almost a year in order to get a wide enough variety of temperatures. Most such tests, therefore, are run at a single value of cooling air temperature, and, at most, a few different values of carburetor air temperature. This explains why valuable data on this subject are so scarce.

It should be said in passing, that the other two methods—propeller-load and full-throttle variable speed methods—both requiring variations in load and speed—are almost never used in fuel testing of multi-cylinder air-cooled engines. There are three reasons for this. In the first place, the airplane engine is inevitably a constant speed-constant load machine, changes in these factors coming only in rare instances while in flight. Hence, it is most desirable to test for fuel requirements under conditions simulating constant load such as occur when climbing close to sea-level. In the second place, it has long been known that detonation in an engine is dependent to a considerable extent upon the crankshaft speed. Thirdly, any variation in speed changes the temperature of the cylinder. It has recently been shown by the admirable researches of Heron at Wright Field, that the cylinder temperature has a very important influence upon the anti-knock value of a fuel or dope, and, most important, this influence varies greatly for the different anti-knocks. Any change in speed or load results in a corresponding change in cylinder temperature, and this increase, in the case of the air-cooled engine, is beyond the control of the operator. Obviously, then, change in speed or load, by resulting in changes in temperature, introduces uncontrollable variables in the anti-knock values of the compared fuels. Besides, it is a fundamental principle of experimental procedure that that test is most reliable which has the fewest variables to control.

In the water-cooled engine, however, the temperature of the water in the jacket can be accurately controlled at all speeds and loads. Since, as is well known, the wall metal of the cylinders, except for the infinitesimally thin inner skin, has practically the temperature of the surrounding water, it is possible to keep the cylinder temperature very nearly constant throughout the range of variable speeds and loads.

Therefore, it is permissible to use the propeller-load method in the testing of water-cooled engines.

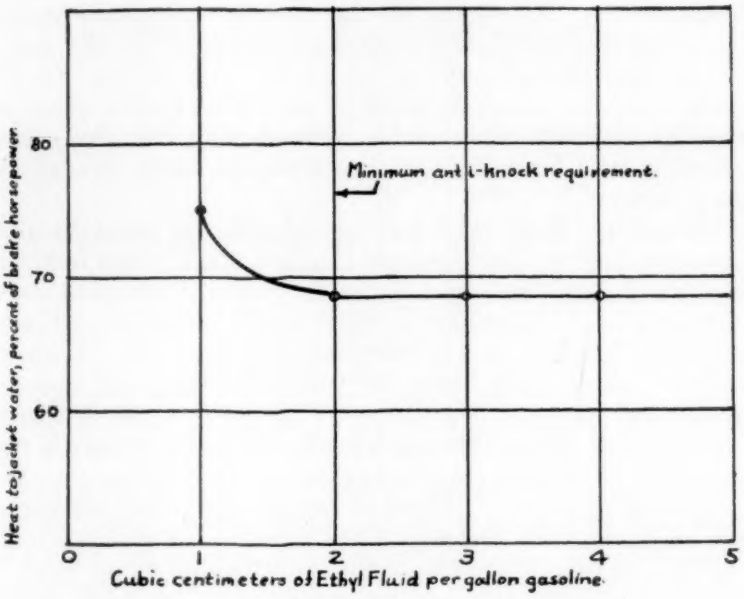
The full-throttle, constant speed methods are used less frequently than the variable throttle test for reasons which will be disclosed subsequently. If the cylinder wall temperature is to be kept constant, the heat rejected to the jacket water must vary. This heat rejection is, therefore, the control used in fuel testing of water-cooled engines. Constant cylinder temperature is most readily maintained by a constant temperature of the water at the outlet from the jacket. Hence, as the heat input to the cylinder wall rises, for any reason, either the rate of water-flow will be increased or its temperature at the jacket inlet will have to be decreased, so that it absorbs the increased heat being transferred without permitting an increase in the metal temperature. Consequently, the change in heat rejected, measured as B.T.U.'s per minute (the product of pounds of water flowing per minute by the rise in temperature, degrees F., between inlet and outlet) is a true measure of the change in heat input to the cylinder wall.

The laboratory mentioned uses the heat rejection as a percentage of the heat transformed into brake horsepower. One horsepower equals 42.42 B.T.U. per minute so that the heat transformed into power equals $42.42 \times$ B.H.P. ($B.T.U._1$). Heat rejected to the jacket equals pounds of water per minute times temperature rise, degrees F. ($B.T.U._2$ per minute). Therefore, percentage heat rejected equals $B.T.U._2$ divided by $B.T.U._1$.

Suppose, then, that the full-power, constant speed test be tried as discussed for air-cooled engines, all conditions except that of anti-knock content of fuel being constant. As we decrease the anti-knock value, the heat rejected to the cylinder wall (and therefore to jacket water) remains constant so long as no detonation takes place; so does the B.H.P. output. Now, for centrifugal water pumps, the mass-flow of water in pounds per minute varies directly as the crankshaft speed, so that with any given speed, the water flow-rate is constant. If, therefore, detonation should set in and the mean or maximum temperature of the cycle increase, the cylinder wall temperature can be kept at a constant value

only by increasing the temperature difference between water into and water out of the jacket. The water-out temperature must be kept constant; therefore, the water entering the jacket must be cooled. In this way, the increased heat rejection caused by detonation is taken care of by an increased temperature difference with the water mass flow-rate kept constant. A curve resulting from such a test is given in Fig. 4. The interpretation is similar to that used in the case

FIG. 4.



of air-cooled engines. The Ethyl Fluid concentration at which the jacket water heat rejection takes a sudden rise is the minimum fuel requirement. We must, of course, have due regard for the base fuel used.[1]

The method using speed variation at full-throttle is of no more value for water-cooled than for air-cooled engines. It is well known that a change in crankshaft speed affects the tendency to detonate. Whether the effect of increased speed is to reduce or increase this tendency depends upon a number of different factors which will be discussed subsequently.

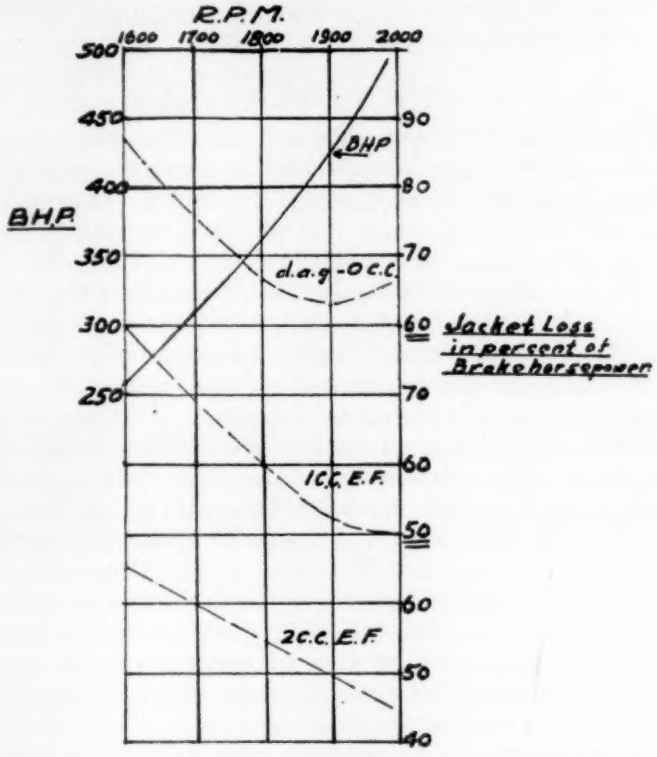
But the fact remains that change in speed changes the detonation tendency and its variation is, therefore, invalidated in testing for anti-knock requirements at full-throttle power.

This same laboratory usually uses the propeller-load method. In this case, engine speed and power are simultaneously varied (by throttle adjustment) for any given fuel, with all other controls constant including jacket exit temperature. In the case of airplane engines this process is simplified by operating on a torque stand with a propeller taking the load. The propeller is set to take the full-open throttle power developed by the engine at the desired maximum speed. Then propeller-load speed variations are automatically made by closing or opening the throttle. On electric cradle dynamometers, however, the load and the throttle position must be simultaneously varied remembering that the power absorbed by a propeller varies as the cube of its revolutions per minute.

Assuming, then, that the operation is on propeller-load variation, any increase in speed means a much larger increase in power. It will be found that so long as no detonation takes place the heat rejection to jacket water, relative to brake horsepower, is inversely proportional to the speed. As soon, however, as knocking sets in, this ratio takes an upward course and starts to increase with further increase in speed. The speed at which this fish-hook in the curve occurs is the maximum throttle opening allowable on this fuel for the propeller setting chosen. A fuel of better anti-knock properties will allow a further opening of the throttle before detonation begins. Finally, a fuel whose anti-knock value is high enough to permit full-throttle operation will show no hook in its curve. Such a set of curves is seen in Fig. 5. The fuels giving the hooked curves will allow knocking before full-throttle is reached; the fuel of lowest dope-concentration which will give a straight line or a hookless curve is the minimum anti-knock requirement for this engine.

This method is superior to the full-throttle-constant speed test in that it allows the investigator to ascertain to what extent of loading a certain fuel can be used in an engine. A fuel, for instance, which causes a fish-hook in the heat rejection curve at three-quarters full-throttle power cannot be

FIG. 5.



used safely beyond that point. Therefore, if such a fuel is the only kind available, the engine must be throttled to 75 per cent. full power to avoid detonation. The advantage from the standpoint of safety, when an untried fuel is used in an engine whose characteristics are unknown, is obvious. The propeller-load method is not usable with air-cooled engines for the reason that the cylinder wall temperatures are uncontrollable. A change in speed with its attendant change in load carries with it a variation in the cylinder temperature which is dependent upon both speed and load. Inasmuch as consistent, reliable anti-knock tests demand constant cylinder temperatures, both load and speed should be kept constant for air-cooled engines. This means the use of a full-p wer-constant speed test. On the other hand, the temperature of

the water-cooled cylinder is completely under control. Consequently, the inherent advantages of the propeller-load test can be utilized in this case.

III. A STUDY OF SOME TEST RESULTS.

To my knowledge no attempt has ever been made to correlate all the test results in order to definitely establish the fuel requirements of multi-cylinder engines. Nor will any such attempt be made in this article because, as I have already indicated earlier, it is all but impossible. Too many variables govern the anti-knock requirements of the different engines. The operating speeds, cylinder size, compression ratio, supercharging ratio, cooling characteristics, fuel consumptions, atmospheric conditions, and above all, general cylinder, piston and valve system designs—all these and many more have influence upon the initiation of detonation with a fuel of any given anti-knock value. Therefore, it is practically impossible to pick any one of these factors, even the compression ratio, and say that for a given value, a given fuel is required. Only for a line of engines which are exactly similar in every other respect and vary only in the one used as criterion can such a tabulation be made and even then it is only approximate. Moreover, as pointed out in previous articles,[1, 2] the base fuels play an exceedingly important part in the Ethyl Fluid requirement, and such base gasolines are rarely equivalent in anti-knock effectiveness in different parts of the country or even in the same locality at different times.

I have already pointed out the intimate connection between the solution of the fuel requirement problem and the study of the power characteristics of the engine. The problem, then, requires an analysis of the way in which those factors which influence the power output affect the knocking tendency of the engine. The magnitude of the problem can be judged from the data tabulated in Table 1. These data give results obtained by the various Government laboratories for a number of service engines, both air and water-cooled. Two classes of influences upon performance are recognizable. One includes such factors as atmospheric conditions and cylinder and piston design, which are beyond the control of

the operator. Let us neglect, for the time, these factors, which serve merely to further complicate the problem, and consider the variation in required anti-knock fuel value with variation in the controllable operating conditions.

These factors as ordinarily considered are four in number: the brake mean effective pressure, specific fuel consumption, crankshaft speed, and jacket water or cylinder temperature. (As a matter of fact we will find that the uncontrollable factors cannot be entirely neglected because variation in some of the four factors just named may be easily caused by a change in an uncontrollable one.) Most of the data in the table were gathered over a period of several years during which the anti-knock value of the aviation gasolines was changing. For the past four or five years, the quality of the Navy Standard East Coast Aviation Gasoline improved at the rate of about $1\frac{1}{2}$ cubic centimeters Ethyl Fluid per year. For instance, the 1931 grade was $1\frac{1}{2}$ c.c. better than the 1930 grade, which in turn was better than the 1929 grade by a like amount. No attempts were made to find the anti-knock value of these fuels on a standard basis such as the Octane-Heptane ratio. Nor has the influence of additions of Ethyl Fluid to such fuels been evaluated on such a scale. (Comparing its performance with that of fuels of known ratings, the present Navy Standard Aviation Gasoline is judged to

TABLE I.

Liquid-Cooled Engines.

Engine.	Jacket T° F.	Comp. Ratio.	R.p.m.	B.M.E.P.	Fuel Cons.	Fuel Reqd.	Octane-Heptane Rating.
Curtiss D–12.....	180	5.6	1900	138	.52	1*	48–52
	180	5.6	2300	130	.50	1*	48–52
	180	7.3	2300	152	.45	2*	77–23
	300	5.6	2300	127	.44	3*	73–27
	300	7.3	2300	144	.41	4*	91– 9
Curtiss V–1570.....	180	5.8	2400	130	.47	5*	58–42
	180	8.3	2400	147	.41	4*	88–12
	180	5.8	2400	178	.53	4*	88–12**
	180	5.8	2400	170	.45	4*	88–12**
	180	5.8	2400	126	.49	6*	75–25
	300	5.8	2400	121	.48	6*	75–25
	300	5.8	2400	122	.53	6*	75–25
Packard 2A1500.....	170	5.5	2100	128	.57	7*(1927)	
Packard 3A2500.....	170	5.5	2000	118	.57	8*(1927)	

TABLE I—*Continued*

Air-Cooled Engines.

Engine.	Comp. Ratio.	R.p.m.	B.M.E.P.	Fuel Cons.	Fuel Reqd.	Supercharger Speed Ratio.
Wright R-760	5.1	1800			1*	7.05
Wright R-1750	5.2	1900	130	.52	3*	
	5.0	1900	121	.64	7*(1930)	8.04
	8.0	1900	144	.45	9*	
	7.8	1900	145	.57	10*	7.4
Wright V-1460	5.3	2500	126	.54	11*(1928)	
P & W R-1340	5.16	1900	124	.55	7*(1928)	7.0
P & W R-1690A1	5.0	1900	131	.55	7*(1930)	7.0
Wright R-1820E	5.1	1900	140	.57	7*(1931)	10.5
Wright R-975					12*(1931)	
Bliss Jupiter	5.3	1900	113	.49	12*(1931)	none
Bristol Jupiter	5.0	1700	114	.52	7*(1929)	none
Curtiss R-600	5.25	1800	122	.50	13*(1929)	none
LeBlond "60"	5.6	2000	105	.54	12*(1928)	none
Comet	5.4	1900	116	.53	12*(1930)	none
American Cirrus	5.4	2100	115	.54	12*(1930)	none
American Cirrus	5.4	2100	137	.55	8*(1930)	to man. pressure of 6 inches, Hg.
P & W R-1340-D	5.25	2200	125	.57	12*(1930)	7.0
	6.0	2200	132	.55	13*(1930)	7.0
	5.25	2100	126	.56	13*(1930)	10.0
	6.0	2100	146	.55	7*(1930)	10.0
	6.0	2200	135	.52	13*(1930)	10.0

References to Table I:

* 1. Mid continent domestic aviation gasoline.
2. Mid cont. d.a.g. + 4 c.c. Ethyl Lead per gallon.
3. Mid cont. d.a.g. + 2 c.c. Ethyl Lead.
4. California Aviation Gasoline + 6 c.c. Ethyl Lead.
5. Mid cont. d.a.g. + ½ c.c. Ethyl Lead.
6. Mid cont. d.a.g. + 3 c.c. Ethyl Lead.
7. East Coast Navy Standard d.a.g. + 2 c.c. Ethyl Fluid.
8. East Coast Navy Std. d.a.g. + 4 c.c. Ethyl Fluid.
9. 70 per cent. California d.a.g. + 30 per cent. benzol + 3 c.c. Ethyl Fluid.
10. 50 per cent. Naphtha + 50 per cent. benzol + 5.5 c.c. Ethyl Fluid.
11. East Coast d.a.g. + 5 c.c. Ethyl Fluid.
12. Unblended East Coast d.a.g.
13. East Coast d.a.g. + 1 c.c. Ethyl Fluid.

Note: Number in parentheses refers to year in which gasoline was produced.

** Supercharged to a manifold pressure of 12 inches, mercury.

have a 74 Octane Number, about equal to the Ethyl Gasoline Standard.) But if we cannot say that a given engine under such and such conditions will require a definite anti-knock

quality (without specific experimental determination of the fact), it is at least possible for us to point out the way in which the quality requirement will move with any change in certain important operating conditions.

1. Effect of Change in B.M.E.P.

We know from our ordinary experience that the primary condition affecting the anti-knock requirement is the compression pressure. Whether a change in this factor is the result of a change in compression ratio or in volumetric efficiency is immaterial so far as its effect upon detonation is concerned. But in the course of ordinary operation, the compression pressure is not easily measurable nor is it usually considered important as an indication of the engine's output performance. With any given compression ratio, under normally constant intake conditions, indicated and brake mean effective pressures are functions of the compression pressure, however varied. The brake mean effective pressure is, moreover, easily measured and a direct index to performance. It is, therefore, desirable to replace the factor of compression pressure by that of B.M.E.P.

It should be carefully noted here that the problem of the connection between the B.M.E.P. and anti-knock requirements naturally divides itself into several distinct phases. There are, to begin with, two large classifications into which engine operations fall: one, in which operation is at full-open throttle; the other, in which operation is at some part throttle position, capable of being varied, for example, to maintain the power more or less constant. It is also obvious that there are two other main classifications—namely, supercharged and non-supercharged. In the latter, the pressure of the charge entering the cylinder is somewhat lower than atmospheric because of the loss through the intake system. In the former, some or all of this pressure drop is recovered in some manner, or the intake pressure may, indeed, be greatly augmented beyond atmospheric. Now in all of these cases, a change in the B.M.E.P. is affected by any one or all of three ways: a change in the volumetric efficiency; a change in the compression ratio; and a change in the manifold air density by either supercharging or a change in the carburetor

inlet air conditions. The effect of a change in the B.M.E.P. upon the anti-knock requirements depends upon the mode of that change. The problem is further complicated when the agent is a change in volumetric efficiency, depending upon whether this factor is changed by throttle movement, mechanical supercharging or by atmospheric conditions, which unfortunately are largely uncontrollable.

At this point, we may turn again to our table with some understanding of the apparently jumbled and unrelated mass of data. For simplicity, we will consider each of the first set of classifications separately. Consider the constant throttle engine. It is clear from this table as it is from actual practice that an increase in the brake mean effective pressure for a given engine, in general, demands an improvement of the anti-knock quality of the fuel, provided, that the quality in use is maintained at the minimum required for the given B.M.E.P. In reality it is the indicated pressure which governs the detonation tendency, but since it is brake power in which we are interested, and since, moreover, the mechanical efficiency is nearly the same for all modern engines under similar conditions and with similar supercharging systems, we are justified in using the B.M.E.P. in measuring the effect of output upon fuel requirements. Normally, it appears to make no difference how this increase in B.M.E.P. is brought about, whether by increase in the compression ratio, in volumetric efficiency, or in supercharging or all three. It alone, as a measure of the maximum compression and explosion pressures, has usually been considered of importance in the matter of fuel quality. It follows, as a matter of course, that in such an engine throttling will reduce the B.M.E.P. and so reduce the anti-knock requirement.

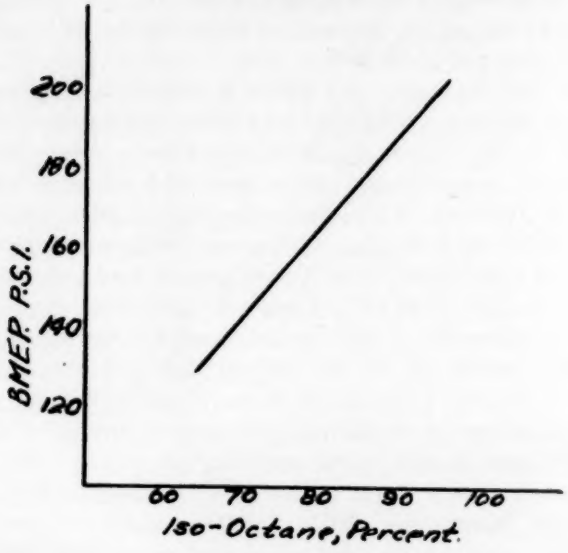
In view of what has already been said, the foregoing statement should not be construed as meaning that a given increase in the B.M.E.P. will demand a given increase in the fuel quality whether the result of an increase in compression ratio or volumetric efficiency. This, obviously, is far from the case as we shall see later. But, as a general statement of our experience, it usually holds quite well that when we increase the B.M.E.P. of an engine, we need a more or less proportionately better anti-knock quality in our fuel. Every-

body knows that with a given compression ratio, detonation can be suppressed by merely throttling, or changing the speed, or reducing the amount of supercharge or in some such way reducing the B.M.E.P.

Thus, for example, a Curtiss Conqueror Engine with a 5.8 compression ratio, unsupercharged, required a fuel quality equal to a 75 Octane-25 Heptane ratio. When this same engine was supercharged to a manifold pressure of twelve inches of mercury, with the same speed and jacket water temperature, and almost the same fuel consumption, the requirement mounted very considerably to an 88 Octane-12 Heptane ratio. The only thing changed was the B.M.E.P. As another example, take the American Cirrus Engine. This 4-cylinder, in-line, air-cooled engine operated without detonation on undoped 1930 grade East Coast domestic aviation gasoline, giving a B.M.E.P. of 115 pounds. When the B.M.E.P. was raised, by supercharging, to 137 pounds, the dope-concentration required was 4 c.c. of tetra-ethyl lead per gallon. Is it possible, then, to formulate a general rule connecting anti-knock value requirement with B.M.E.P., other operating conditions remaining substantially constant? Taylor [3] gives the curve shown in Fig. 6, purporting to show the possible increase in B.M.E.P. with an increase in the Octane number of the fuel. Since the author gave no further data regarding the source of his curve, we can assume it to apply to a normal case, i.e., an engine operating at full-open throttle. Later, we will see how well it applies to the other case in our category. The data in our table, added to what I have already said, show that this curve is a highly hypothetical case and can be applied if at all only with a very restricting set of limitations. Consider the two possible ways in which the B.M.E.P. represented in this curve could have been raised. Consider further that the throttle position was constant, or, for simplicity's sake, that it was wide open. In one way, the compression ratio was increased. In the other, the volumetric efficiency (by means of supercharging) was increased. In a third possible way (a hypothetical method) the temperature of the intake charge was reduced (causing, thereby, a reduction in the volumetric efficiency).

Before considering the problem further, let us review some

FIG. 6.



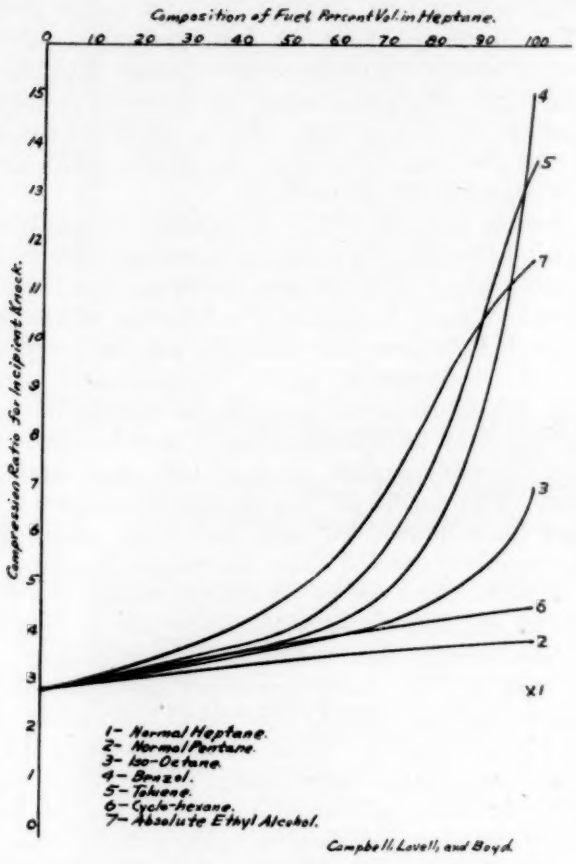
elementary facts concerning knocking in the engine cylinder. The rate at which chemical reaction goes on during combustion is enormously sensitive to changes in temperature. It also varies as the initial pressures or concentrations. If we measure the velocity of this reaction by the rate of movement of the flame in a simple cylinder, these conditions change. The great influence of temperature still remains, but pressure no longer has any measurable effect.[4] But, on the other hand, the phenomenon of detonation in a bomb or knocking in the engine cylinder is a vastly more complex event than chemical reaction. As I have already said, our experience has been that the controlling factor in inducing knock when the general operating conditions have been maintained constant, is the compression pressure.[2] No other fact has been established so fundamentally in the fuel testing art. The influence of temperature, however, is by no means quantitatively definite. An increase in the initial temperature of the charge increases the knocking tendency of a fuel, but its influence is so irregular that it cannot be embodied in any mathematical law such as is probably possible for the pressure

effect. For instance, the rate of increase in the intensity of knock with temperature increase is very much greater at high initial pressures than at low pressures, where the sensitivity of knock to temperature change is quite small. Nevertheless, the effect is present and must be considered in any discussion of the subject. As to which factor is more important in the engine cylinder we cannot tell. It is impossible to separate the two effects.

It is possible that the effects of pressure are really secondary, operating through the changes in temperature caused by pressure variations. Nevertheless, the intensity of detonation in the engine cylinder is definitely a function of compression pressure, and I believe the relation can be expressed in mathematical equations for any given anti-knock or type of anti-knock. It is, therefore, possible to express the required concentration of an anti-knock dope in any fuel as a definite function of the compression pressure for equal intensities of detonation. The nature of this functional relation has been determined for a number of fuels and under many different sets of operating controls. The functional character of this relation, that is, the type of equations connecting the concentration of anti-knock with the variation in compression pressure, has been at least qualitatively established, but the arbitrary constants in these equations have been found to depend upon the controls and method of tests used.[1, 2] The curves in Fig. 7 show the relationship for several important anti-knocks in terms of compression ratio.[5] The nature of the function in terms of compression pressure can be easily obtained if it is assumed that the volumetric efficiency and the carburetor intake conditions were the same for all the tests.

The important thing here is that for none of these fuels is the function a linear one. Moreover, if these curves are plotted on logarithmic cross-section paper, it will be found that none of them can be expressed by a simple exponential equation. I have found in an analysis, as yet unpublished, that only for concentrated lead tetraethyl can the relation be so stated. For all other anti-knocks, including the various Ethyl Fluid mixtures, the relation between concentration and compression ratio or compression pressure is expressible in a

FIG. 7.



series of equations each operating between definite limits of concentration. This is especially true of the Octane-Heptane ratio. In the face of these facts, it is difficult to see how the simple curve in Fig. 6 was derived. For it to be valid, the B.M.E.P. must bear the same functional relationship to compression pressure as does the Octane concentration in Heptane. That this is not so will be obvious from a thermodynamic analysis of the former function.

1A. Change in Compression Ratio.

Experiments in explosion bombs have shown that the initiation of knock is apparently a function of the maximum indicated conditions of explosion pressure and temperature. With the charge mixture strength at a constant value, and the cylinder walls at a constant temperature, the maximum explosive pressure is directly proportional to the precombustion pressure. In an engine cylinder, this is strictly true only for the condition of constant compression ratio, since the factors of thermal efficiency, amount of clearance space dilution and others which tend to change the temperature rise during combustion, act to modify the proportionality. Thus, if

Pi = initial pressure, p.s.i.,
Ti = initial temperature, ° F. abs.,
Pc = compression pressure, p.s.i.,
Tc = compression temperature, ° F. abs.,
Pa = atmospheric pressure, p.s.i. = pressure at carburetor inlet,
Ta = atmospheric temperature, ° F. abs. = temperature at carburetor inlet,
Ev = volumetric efficiency, referred to carburetor inlet conditions,
Tm = maximum explosion temperature, ° F. abs.,
Pm = maximum explosion pressure, p.s.i.,
r = compression volume ratio,
n = expansion or compression line exponent, representing the ratio of specific heat of the gases at constant pressure to that at constant volume,
M = rise in mixture temperature during explosion, ° F. $(= Tm - Tc)$,

we have for a given value of Ta,

$$Pc = Ev \times Pa \times r^n = Pi \times r^n. \tag{1}$$

Also,

$$Tc = Ti \times r^{n-1} \tag{2}$$

$$Pm = Pc\frac{(Tc + M)}{Tc} = Pc\left(1 + \frac{M}{Tc}\right) \tag{3}$$

Of course, we are here assuming that all fuel is burned at top dead center and there are no heat losses. But before deciding that this is too far-fetched an assumption, consider the fact that experiment shows that practically all fuels give the same maximum power and require the same optimum spark advance for the same compression ratio. Thus, there is evidence that this assumption is accurate enough to allow a good comparison for the various fuels.

Our problem now is to find out how those factors which experience tells us influence the knocking tendency of an engine are affected by a change in compression ratio. This phase of the problem must be analyzed from the standpoint of the classical thermodynamics because there are no extensive indicator card data for high speed engines. But any such thermodynamic treatment is hypothetical because it starts with assumptions which only approximate true conditions. Thus, many different treatments are possible depending upon the sets of assumptions made at the start. I have thought it desirable to make several different series of calculations in order to show how the difference in initial assumptions affects comparative results.

As a matter of fact, the problem is not quite so simple as the foregoing formulas indicate, since the exponent n is in itself a complex function of the temperature and nature of the working gases. To use the simple relations in (1), (2), and (3) n must be determined empirically. As I have just stated, in the high-speed engine this is by no means easy since an accurate value of n is best derived from indicator card data. Treatment of this phase of the problem by the classical thermodynamics in which the factors of heat loss, dissociation and dilution are neglected yields the following relations.[6] In this treatment, also, the nature of the working fluid and its variation during the cycle are unknown, but its specific heats are assumed to vary in accordance with the following equations:

$$Cv = A + BT,$$
$$Cp = A' + BT,$$

where Cv = specific heat at constant volume heating, and Cp, at constant pressure. A, A' and B are constants and T is

absolute temperature at which C is desired. Let Fig. 8 be an indicator card for such an engine. It can be shown that

$$PV^{A'/A}e^{BT/A} = k,$$

where e = Naperian logarithmic base = 2.718. Or

$$PaVa^n e^{BTa/A} = PcVc^n e^{BTc/A}.$$

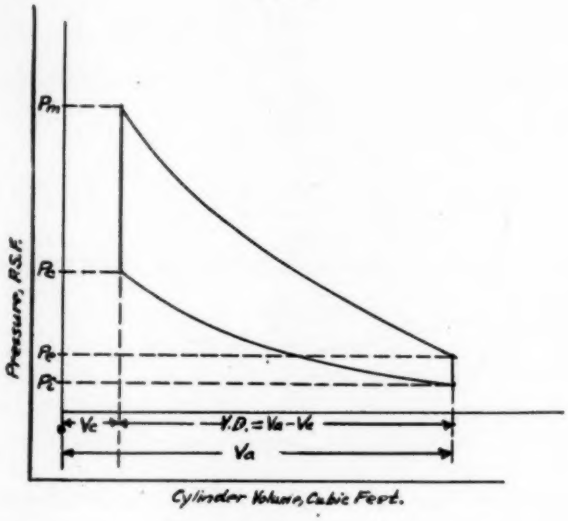
Or

$$\frac{Pc}{Pa} = \left(\frac{Va}{Vc}\right)^n e^{B(Ta-Tc)/A}. \tag{4}$$

Also

$$\frac{Tc}{Ta} = \left(\frac{Va}{Vc}\right)^{n-1} e^{B(Ta-Tc)/A}$$

FIG. 8.



$$= \left(\frac{Pc}{Pa}\right)^{(n-1)/n} e^{B(Ta-Tc)/An}. \tag{5}$$

Also

$$\frac{Pc}{Pa} = \left(\frac{Va}{Vc}\right)^n e^{B(PaVa-PcVc)/RA}, \tag{6}$$

where R = gas constant = $J(A' - A)$ and J = 778 = Joule's

heat equivalent. Now if Q_1 = heat added at constant volume

$$Q_1 = \int CvdT = (Tm - Tc)\left[A + \frac{B}{2}(Tm + Tc) \right]$$

or

$$Tm = \sqrt{\frac{2}{B}\left[Q_1 + \left(A + \frac{B}{2} Tc \right) Tc + \left(\frac{A}{B} \right)^2 \right]} - \frac{A}{B}. \quad (7)$$

Finally,

$$Pm = Pc\frac{Tm}{Tc}. \quad (8)$$

Equation (8) is recognizable as identical with (3). If Q_2 equals the heat abstracted during the cooling of the exhaust gases to the initial temperature, the net work of the cycle is obviously

$$W = J(Q_1 - Q_2) \text{ in foot lbs.} \quad (9)$$

Then,

$$\text{I.M.E.P.} = \frac{\text{net work}}{\text{volumetric displacement}}$$

$$= \frac{J(Q_1 - Q_2)}{144 \times (Va - Vc)} \text{ P.S.I.,} \quad (10)$$

where Va = total cylinder volume and Vc = clearance volume in cubic feet.

Assume now that

Pa = 14.7 p.s.i. abs. = Pi,
Ta = 520° F. abs. = Ti, constant with change in r,
$Va - Vc$ = displacement volume = 0.1 cubic foot.

Following Clerk, for the working fluid in an Otto cycle engine, assume:

$$Cv = 0.1801 + 0.0000283T,$$
$$Cp = 0.2511 + 0.0000283T.$$

More recent values are probably more accurate but since our starting assumptions disregard such important factors as heat loss, more accurate specific heat data are of no great moment to our present case. What we are concerned with

here are comparative values and functional relationships which are slightly if at all changed by the particular values of specific heats used. Continuing, then, we find

$n = A'/A = 1.395$,
$R = 55.2$.
Weight of gas in cylinder at Ta and $Pa = 0.0098$ pound.

If we assume an air-fuel ratio of 15 to 1, the weight of fuel used per cycle equals 0.000613 pound. Then, assuming a low heat value of 20,000 B.T.U. per pound, $Q_1 = 12.3$ B.T.U. per cycle = 1250 B.T.U. per pound of gas mixture. Also

$$Va = 0.1 + Vc \text{ cubic foot},$$
$$Vc = 0.1/r - 1 \text{ cubic foot}.$$

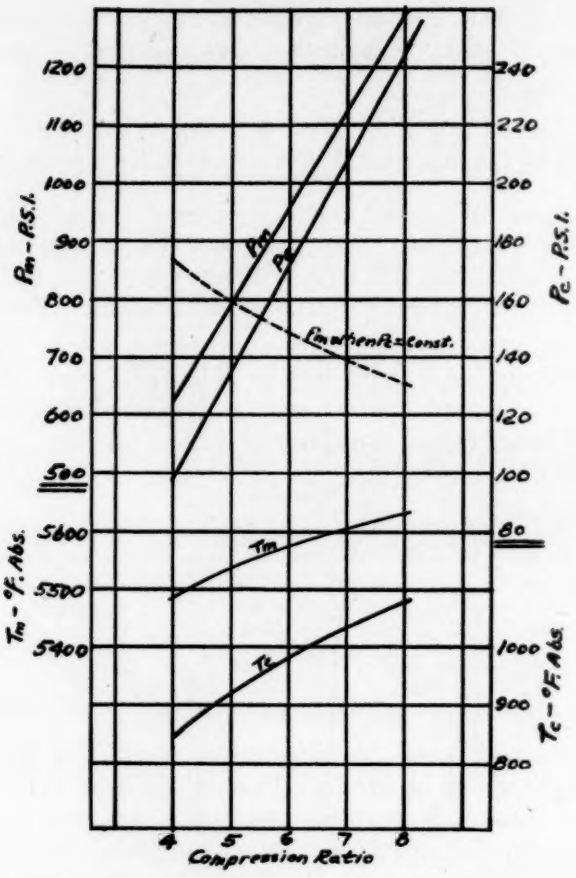
The calculated values are given in table 2 and the important factors plotted in Fig. 9.

TABLE 2.

r.	$Tc°$ F.	Pc P.S.I.	$Tm°$ F.	Pm P.S.I.	I.M.E.P. P.S.I.
4	850	97	5490	627	216
5	925	132	5540	790	228
6	980	169	5570	960	236
7	1040	208	5610	1120	243
8	1080	247	5630	1290	250

I mentioned earlier an alternative method of calculating the data, in which an empirical value of n was derived from indicator cards. Sparrow [7] uses the value $n = 1.3$. The initial assumptions are: $Pi = Pa = 14.7$ p.s.i.; $Ev = 100$ per cent.; $M = 2700°$ C.; Ti is figured by assuming the 100 per cent. volumetric efficiency at 320° C. absolute, while the residual exhaust gases are assumed as completely filling the clearance space at atmospheric pressure and 1273° C. abs. Since I am aiming simply at a comparison here, I am neglecting certain factors such as the change in temperature rise which should take place with change in compression ratio. Similarly, increased compression ratios result in decreased exhaust gas temperatures. But such changes are accompanied by compensating changes (such as rise in specific heats, dissociation, etc.) with the results that our comparisons are nearly exact regardless of our assumptions.

FIG. 9.

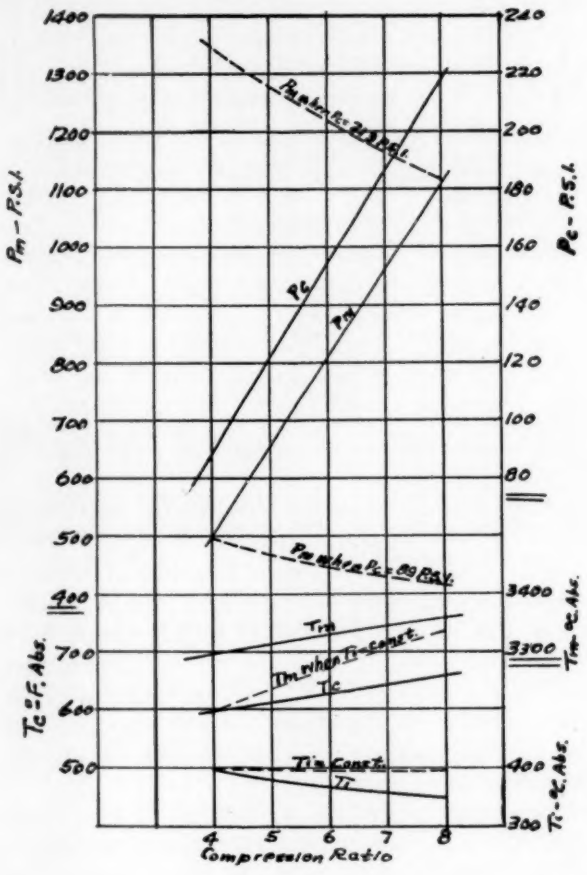


The calculated data are listed in Table 3 and plotted in Fig. 10. Although an arbitrary value of n was used whose

TABLE 3.

r.	Ti° C.	Tc° C.	Pc P.S.I.	Pm P.S.I.	Tm° C.	I.M.E.P. P.S.I.
4	393	595	89	494	3295	146
5	376	610	119	645	3310	159
6	365	625	151	806	3325	172
7	358	643	185	960	3343	180
8	353	660	219	1115	3360	188

FIG. 10.



value was probably no closer to the true value than the previous calculations gave, this method, in allowing for the effect of residual exhaust gases upon initial temperature, is nearer the true condition than the other. It will be seen that *Ti* falls with an increase in *r* principally because (a) the temperature of the exhaust gas falls also, and (b) the smaller clearance space reduces the amount of residual hot gases available for raising *Ta* to *Ti*.

The I.M.E.P. was calculated from the net work done by assuming a card factor of 0.95. Then, it can be shown that

$$\text{I.M.E.P.} = \frac{.95}{r-1}\left[\frac{Pm}{n-1}\left(1-\frac{1}{r^{n-1}}\right) - \frac{Pc}{n-1}\left(1-\frac{1}{r^{n-1}}\right)\right]. \quad (11)$$

For purposes of further comparison, Table 4 gives data as taken from Goodenough and Baker,[8] who present the most

TABLE 4.

r.	$Ti°$ F.	$Tc°$ F.	Pc P.S.I.	$Tm°$ F.	Pm P.S.I.	I.M.E.P. P.S.I.
3.5	715	1076	77.4	4979	383.2	140.2
5.0	683	1081	124.5	5053	622.9	177.7
6.5	605	1117	176.4	5108	863.4	202.7
8.0	586	1174	235.6	5150	1114.4	221.2

Note: 100 per cent. theoretical air assumed. $Pi = 14.7$ p.s.i.

refined method of ideal cycle analysis so far devised. An explanation of this method will not be given since it is a most complicated excursion into the physico-chemical and stoichiometrical phases of combustion, but it is sufficient to say that, so far as the functional relationships go between compression ratio and cyclic pressures and temperatures, the results do not differ greatly as between this method and the two simpler sets of calculations. This is especially significant since the initial assumptions are purely hypothetical but widely different in each case.

Now, from our equations as well as from the curves on Figs. 9 and 10, we can see that as the compression ratio increases, the compression pressure rises very much more rapidly than the compression temperature, and, similarly, the maximum explosive pressure goes up enormously faster than the corresponding temperature. In fact, with similar engines at full-throttle, this explosive temperature is relatively constant with variation in compression ratio as compared to the explosion pressure. This effect is further strengthened in such cases by the well known fact that the initial or suction temperature falls with a rise in compression ratio because of a smaller amount of hot residual exhaust gases left to mix with and heat the fresh charge.

In fact, both Pm and Pc are, within close limits, linear functions of r (that is, the n in equation (1) has an effect not much greater than unity) whereas Tc and Tm vary as r^m where m is much less than 1. It is interesting also to note that the equations of Pc and Pm as functions of r are not greatly changed by changes in Ti, although Tm rises at a much greater rate when Ti is constant than when Ti falls with increase in r. This is clearly shown in Fig. 12 where Pm as a function of Pc is apparently unchanged by differences in the initial assumptions. The curve numbers on these figures, and those following, represent the tables from which the data were taken.

The solid curves in Fig. 11 show how variations in initial assumptions affect the mode of variation of I.M.E.P. with r, while the lower curves in Fig. 12 do the same for I.M.E.P. as a function of Pc. The solid line curves in Fig. 13 show I.M.E.P. as a function of Pm under the same conditions. One outstanding conclusion arises, i.e., that whereas changes in initial assumptions result in only a very slight change in the laws governing the variation of Pm and Pc with respect to r, or, relative to each other, the same changes will introduce considerable variations in the nature of I.M.E.P. as a function of either r, Pm or Pc.

Considering, then, the evidence in Figs. 9 and 10, and recalling that according to equations (3) and (8), the rise in pressure during explosion is a function of Pc/Tc, we have considerable ground for concluding that the effect of compression ratio upon detonation is due almost entirely to its effect upon compression and maximum pressures rather than to its effect upon cyclic temperatures, without regard to the initial conditions. All our single cylinder work has clearly substantiated this conclusion, namely, that the same fuel will detonate at practically the same compression pressure regardless of the compression ratio.[1, 2]

Recall, now, my earlier statement that the laws of variation of anti-knock concentration needed to suppress knocking with change in compression ratio or compression pressure are, apparently, unaffected by change in initial operating conditions and, therefore, by analogy, in initial assumptions. It is obvious, then, from these conclusions and from the curves

FIG. 11.

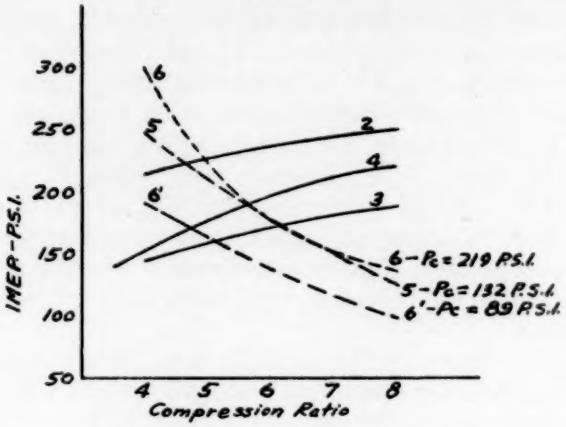
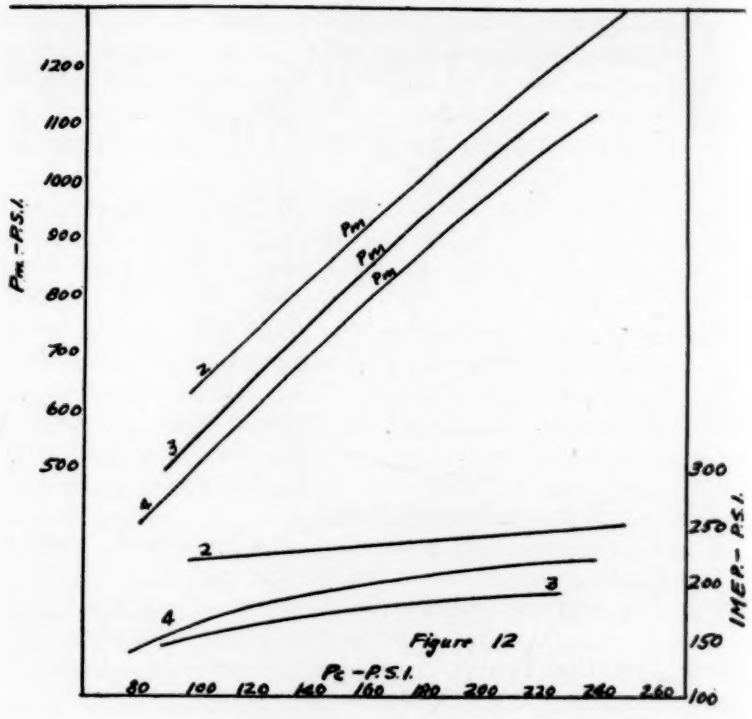
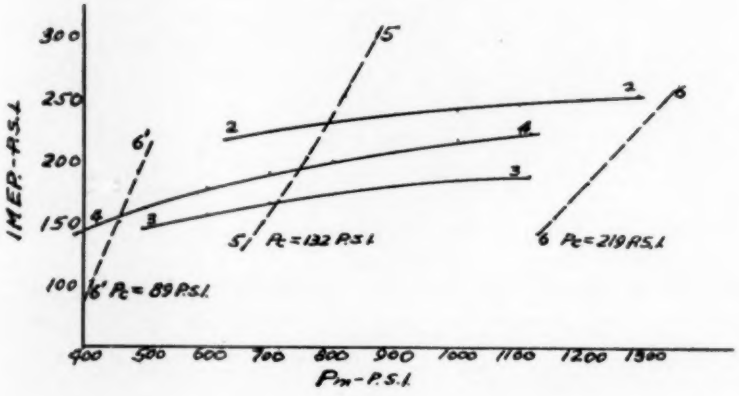

300
250
200
150
100
50
IMEP - P.S.I.
4 5 6 7 8
Compression Ratio
6
5
6'
2
4
3
6 - Pc = 219 P.S.I.
5 - Pc = 132 P.S.I.
6' - Pc = 89 P.S.I.

FIG. 12.


1200
1100
1000
900
800
700
600
500
Pm - P.S.I.
Pm
Pm
Pm
2
3
4
2
3
4
300
250
200
150
100
IMEP - P.S.I.
Figure 12
Pc - P.S.I.
80 100 120 140 160 180 200 220 240 260

in Figs. 11, 12 and 13, that it is impossible to deduce any hypothetical general rule which will predict the Octane rating needed for a given I.M.E.P. at full-throttle operation. The curves in Fig. 14 make this clear.

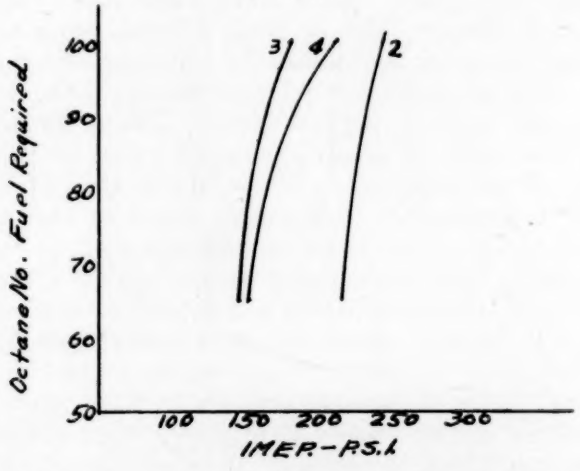
FIG. 13.



It may be argued that I have dealt here with ideal, hypothetical cases. That is true; I have neglected such important factors as heat losses by radiation and wall conduction, and heat suppression due to changes in the nature of the working fluid during the cycle. These factors may decrease the I.M.E.P. of our ideal cycle by as much as fifty per cent. From this point of view, the method of Table 3, in which n is assigned an arbitrary value so that it is an average exponent taken from an indicator card, is the most trustworthy. But, no real importance can be attached to this matter of difference between hypothetical and real cases because, in the first place, the heat suppression and loss factors will vary widely with engine design and operating conditions, and in the second, both the indicator card and its interpretation are subject to large errors when dealing with high speed automotive engines. It is well known that in a real engine n changes in value several times on both the expansion and compression lines, a fact which makes the estimation of I.M.E.P. on any but hypothetical grounds exceedingly complicated if not impossible.

Moreover, if change in our operating or initial conditions changes the I.M.E.P. variation in a real engine, we have, then, a parallel to the effect of change in the initial assumptions of our ideal case, so that the conclusions to be drawn from Figs. 9 to 14 should hold, qualitatively at least, for real as well as hypothetical engines. One other thing is fairly well established. Change in compression ratio has no material effect upon friction horsepower at full-throttle; that is, the mechanical efficiency is increased with increasing compression ratio. It follows, then, that as r increases, the B.M.E.P. will rise at a greater rate than the I.M.E.P. It is obvious that the divergence from a linear relation in Fig. 14 would be greater for a real engine with B.M.E.P. as the abscissa than even in the hypothetical case given. In other words, the relationship expressed in Fig. 6 is true, if at all, only for a case of very special conditions. All the evidence points to the conclusion that the variation in anti-knock requirement with B.M.E.P. must be determined by experiment for each individual engine.

FIG. 14.



We will see later, when I discuss mixture ratio, that this factor further complicates the relation between B.M.E.P. and the Octane requirement. For the present, let it be understood that I am dealing with the mixtures giving theoretically maximum heat output; i.e., chemically correct ratios.

(To be continued.)

NOTES FROM THE U. S. BUREAU OF STANDARDS.*

STANDARD FREQUENCY RADIO BROADCASTING SERVICE.

The Bureau provides a standard frequency service which is broadcast by radio. Since October 1, this service has been given on three days each week, from the Bureau's station WWV, Beltsville, Md., near Washington, D. C. The object of these radio emissions is to provide a standard for scientific or other measurements requiring an accurate radio or audio frequency or time rate. They are likewise useful to radio transmitting stations for adjusting their transmitters to exact frequency, and to the public generally for calibrating frequency standards.

On each Tuesday and Friday the emissions are continuous unmodulated waves (CW); and on each Wednesday they are modulated by an audio frequency. The audio frequency is in general 1,000 cycles per second. (There are no emissions on legal holidays.)

On all emissions three radio carrier frequencies are transmitted as follows: noon to 1 P.M., Eastern Standard Time, 15,000 kc./s. (kilocycles per second); 1:15 to 2:15 P.M., 10,000 kc./s.; 2:30 to 3:30 P.M., 5,000 kc./s.

The emissions on 5,000 kc./s. are particularly useful at distances within a few hundred miles from Washington, those on 10,000 kc./s. are useful for the rest of the United States, and those on 15,000 kc./s. are intended to serve the western half of the United States and to some extent other parts of the world.

During the first five minutes of the one-hour emission on each carrier frequency, announcements are given. For the CW emissions, the announcements are made by telegraphic keying and consist of the station call letters (WWV) and a statement of the frequency; this announcement is repeated every ten minutes. For the modulated emissions, the announcements are made only at the beginning of the hour; they are given by voice and include the station call letters

*Communicated by the director.

and a statement of the carrier frequency and the audio modulation frequency.

Except during the announcements, the CW emissions consist of continuous, unkeyed carrier frequency, giving a continuous beat note in the telephone receiver in heterodyne reception. The radiated power in the CW emissions is 20 kilowatts.

The modulated emissions, except during the voice announcements at the beginning of the hour, consist of an uninterrupted audio frequency superposed on the carrier frequency. The radiated power is only one kilowatt; reception is therefore not as reliable as for the CW emissions of Tuesdays and Fridays; it is hoped to increase the power later. The modulated emissions are somewhat experimental, and for this reason an audio frequency other than 1,000 cycles per second may be used on some occasions. The presence of the audio modulation frequency does not impair the use of the carrier frequency as a standard to the same high accuracy as in the CW emissions.

The accuracy of the frequencies as sent out from the transmitting station is at all times better than a part in five million. Transmission effects in the medium (Doppler effect, fading, etc.) at times may result in slight fluctuations in the frequency as received at a particular place. However, these will practically never impair the reception of the carrier frequency to the accuracy stated. Under some conditions, momentary fluctuations as great as 1 cycle per second may occur in the modulation frequency. It will generally be found possible, however, to use the modulation frequency with an accuracy better than a part in a million by selecting that one of the three carrier frequencies which has the least fading. The use of automatic volume control on the audio frequency will be found helpful.

Information on how to receive and utilize the standard frequency service is given in a pamphlet obtainable on request addressed to the National Bureau of Standards, Washington, D. C. From any single frequency, using harmonic methods, any frequency may be checked.

The Bureau welcomes reports of use and comments upon the standard frequency service. As the modulated emissions

are somewhat experimental, the Bureau is particularly anxious to receive reports from those utilizing them, including: description of method of use; statement of relative fading, intensity, etc., on the three carrier frequencies; and preference as to audio frequency to be furnished. Correspondence should be addressed National Bureau of Standards, Washington, D. C.

A PRACTICAL SYSTEM OF AUTOMATIC RADIO SIGNALS FROM A FREE BALLOON.

A complete system, based on the Olland telemeteorograph, for obtaining signals by means of a radio transmitter, from instruments attached to free balloons, has been constructed at the Bureau. In this way records are obtained instantaneously by a receiver located on the ground. The wave length adopted is 5 meters, permitting convenient use of a half-wave tuned doublet antennas for transmission as well as reception. The radio transmitter is "keyed" in such a way that signals are emitted only during several short contacts per minute, thus greatly reducing the size of the plate batteries required.

In this development the Bureau is working in close cooperation with the Weather Bureau in the belief that the system will prove valuable for obtaining meteorological data at great altitudes. The complete radio apparatus for attachment to a balloon weighs less than two pounds, and preliminary trials show that the signals can be heard clearly at altitudes of 14 miles and at distances of 80 miles. By employing a method of direction finding for the pulses emitted by this radiometeorograph the location of the balloon can be ascertained at the instant any pulse is sent out.

MEASUREMENT OF ALTITUDE IN RECORD FLIGHTS.

Before July 1, 1935 the accredited altitudes in record flights had been determined by the single measurement of the lowest air pressure attained in the flight, converted to altitude by means of the altitude-pressure relation of the standard atmosphere of the Federation Aeronautique (FAI) Internationale.

Since July 1, 1935 the FAI requires that the *actual* altitude of aircraft above sea level shall be determined in flights

above 10,000 meters (32,808 feet) which are made in an effort to establish an international record. The altitude is to be computed from continuous measurements in flight of air pressure and temperature by means of the barometric altitude formula. A meteorograph installed on the aircraft exposed to the free air is specified to be used in making the necessary measurements.

In a paper by W. G. Brombacher of the Bureau at the aeronautic meeting of the American Society of Mechanical Engineers in St. Louis on October 10, a digest of the regulations is presented. Certain requirements appear to be undesirable, notably the requirement that the meteorograph must be installed in airplanes 0.4 of the wing chord in front of the leading edge of the wing. This awkward installation is unnecessary, since a suitable meteorograph can just as well be installed anywhere on the aircraft, where it is exposed to the free air, or, alternatively, indications of instruments installed in the fuselage can be photographically recorded.

In balloons it is difficult to measure air temperature without artificial ventilation. For this reason it is necessary to provide for the use of instruments so equipped, either a meteorograph or an electrical thermometer and an aneroid barometer. If the latter instruments are used, photographic recording of the indications is required.

The regulations specify that instruments shall be calibrated within 15 days before the flight. This short interval is unnecessary to secure accuracy if certain other precautions are taken, and is very inconvenient for flights in an area as large as the United States. It is suggested that the interval be increased to two or three months.

PRODUCTION, HEAT-TREATMENT AND PROPERTIES OF IRON AND STEEL.

The numerous letters of inquiry received by the Bureau for practical information on the production, heat-treatment, and properties of iron and steel are believed to indicate a genuine interest among men in the plant in the underlying principles of processes and manipulations with which they come in daily contact. Many of these inquiries for specific information about iron and steel indicate a desire to undertake ele-

mentary studies of metallurgical processes and materials. In the attempt to meet the needs of a considerable group of such inquiries the Bureau has prepared a concise elementary account of the production, heat treatment, and properties of iron alloys, steel, cast iron, wrought iron, etc., which will appear in its circular series. Particular attention has been given in this account to the theories developed within very recent years of hardening steel and of the role of special alloying elements.

DETERMINATION OF OXYGEN IN STEEL.

Under the joint sponsorship of the National Bureau of Standards and the iron and steel division of the American Institute of Mining and Metallurgical Engineers, an international coöperative study of the various methods which are used for the determination of oxygen in steel is drawing to a close. This project is an attempt to define more precisely than has been possible heretofore the comparative merits and the limitations of each of these analytical methods. Eight steels, each representing a different combination of ferrous and manganous oxides, silica, alumina, and sulphur, within the range of composition of commercial plain-carbon steels, were selected and examined for uniformity of composition. Specimens as nearly identical in composition as possible were prepared and distributed to each of the coöperating laboratories for determination of the oxygen contents by the method or methods preferred in that laboratory. The reports of these analytical results are being made to the Bureau, which is acting as a clearing house in the undertaking.

There are 36 laboratories at present engaged in active participation in the project, 20 in the United States and 16 in foreign countries. Already 25 of the laboratories have submitted their reports, and assembly of the data, classification of results according to the method used, and study of the various procedures for departure from normal has been started. The summary is far from complete and additional reports will be included as they are received. However, the divergence of results which is already evident is ample justification for undertaking the project.

PROPERTIES OF CARBON TOOL STEELS.

The mystery that for many years surrounded differences in hardenability of steels of quite similar compositions has recently been largely removed by the recognition of the influence of austenitic grain-size on hardening characteristics. RP837 in the October number of the Journal of Research deals with the influence of the initial microstructure of tool steels on grain-size and hardening characteristics.

Widely used brands of 1-per cent.-carbon tool steels, produced by one foreign and five domestic manufacturers, were classified according to their depth of hardening. From these brands two steels of widely different depths of hardening were selected. Specimens of these steels were treated so as to have three different initial structures: (*a*) Spheroidized cementite; (*b*) coarse pearlite; and (*c*) sorbite, and a study was made of the effect of these initial structures on the austenitic grain-size and grain-growth, and on the critical cooling rates. These data also made possible a direct comparison of the relation between austenitic grain-size and critical cooling rate of the two steels over a range of quenching temperatures of 773 to 967° C. (1425 to 1775° F.).

A comparison was made of these two steels with respect to their behavior in the transformation temperature range during thermal analysis, relative rates of spheroidization of cementite, Charpy impact strengths, relative susceptibility to grinding cracks, structural normality, hardness on quenching with different rates, performance as lathe tools, and the effect of rate of heating to the hardening temperature on the depth of hardening.

STEEL FOR WITHSTANDING SHOCK LOADS.

Information on the relative resistance to shock loads of carbon steel and of an alloy steel proposed for the construction of large chains for lifting the gates of a dam in the Mississippi river was recently requested of the Bureau. The most convincing way of obtaining such information would be to subject chains of the two types of steel to shock loads and observe their behavior. Such tests were not practicable, however, since the chains were designed to have a lifting capacity of 1,000,000 pounds.

It is known that carbon and some alloy steels, when fractured by a sudden application of load will, under certain conditions, show a fibrous fracture, whereas under other conditions the fracture will be granular and be produced by a considerably smaller shock load. The transition from "fibrous" to "granular" fracture may occur with a temperature drop of the order of 100° F. to 0° F. Other contributing factors are change in size, form, composition, and previous mechanical and thermal treatment. Some of these factors may cause the transition to occur at a higher temperature and some at a lower one. For a structure exposed to atmospheric ranges of temperature, the lower the temperature at which the transition from fibrous to granular fracture of the material occurs, the greater the margin of safety to be expected under shock loads.

Charpy impact tests made on notched-bar specimens of the steels under consideration for the chains, at various temperatures ranging from − 40° C. (− 40° F.) to 100° C. (212° F.), showed that the transition from fibrous to granular fracture occurred at an appreciably lower temperature in the carbon steel than in the alloy steel. Many factors must, of course, be given due consideration in the choice of the steel to be used, but to the extent that the relative shock-resistance of the carbon steel and alloy steel chains can be judged from the results, the tests indicated a greater margin of safety for the carbon steel.

EDUCATIONAL COURSES 1935–1936.

Plans are now being formulated for a number of graduate study courses in physics, mathematics and chemistry, to be given at the Bureau during the coming winter. Courses of this character have been given regularly for the past 27 years, and are recognized by many of the leading universities in allowing credit for advanced degree. Although these courses are planned primarily for members of the staff of the National Bureau of Standards, they are open on the same terms to any person who can furnish the instructor evidence of satisfactory preliminary training.

The Educational Committee has adopted the following two

cycles as constituting the fundamental part of a graduate training in physics.

Physics Cycle:

Theoretical mechanics (due this year).
Electricity and magnetism.
Advanced optics.

Mathematics Cycle:

Theory of functions (due this year).
Differential equations.
Fourier series.

One course of each cycle is normally given each year. However, in view of the fact that substantially all of the present staff of the Bureau has had an opportunity to take each cyclic course, these courses (A and B) will be offered tentatively, to be given only in case the advance registration is sufficient to justify them. Courses C and D are announced without this restriction. The reduced fee of $15.00 per course, initiated last year, and applying to all applicants whether members of the Bureau Staff or not, will be continued.

Course A.—Theoretical mechanics—Dr. R. G. Brickwedde. Sixty lectures given two hours per week throughout the year. The course covers the fundamental principles of kinematics and dynamics. The generalized equations of Lagrange and Hamilton will be derived and their applications illustrated by problems. Special consideration will be given to vibrations and cyclic motions, and to the gyroscope and gyrocompass. A few lectures at the end of the course will be devoted to special relativity and to the fundamental principles of quantum mechanics.

Prequisites: Calculus.

Text: The Dynamics of Particles and of Rigid, Elastic and Fluid Bodies by Arthur Gordon Webster.

Course B.—Theory of functions of a complex variable—Dr. Tobias Dantzig. Sixty lectures given two hours per week throughout the year. The course covers a review of the fundamental mathematical notions and operations used in function theory; a review of the development of the number concept from the integer to the complex number; the funda-

mental theorem of algebra; the Cauchy-Rumann method and conformal representation; the Weirstrass method and infinite series and products, the elementary transcendental functions; beta and gamma functions, elliptic functions; functions defined by differential equations; applications to physical problems, pendulum and gyroscope, planetary motion, potential theory, elasticity and hydro-mechanics etc., with a brief consideration of their application to quantum mechanics. Prerequisites: Trigonometry, analytical geometry and calculus.

Text: Goursat—Hedrick (or equivalent).

Course C.—Introduction to probability and statistics—Dr. W. Edwards Deming. Sixty lectures given two hours per week throughout the year.

First semester—Development of mathematical tools: moments of areas, theory of Sheppard's corrections, interpolation and the calculus of finite differences, the complete and incomplete gamma and beta functions and their tables, moments of more complicated areas. Asymptotic approximations to several events; the history of the normal curve and its tables. Fundamental notions of probability. The ergodic hypothesis and randomness. Sampling.

Second semester—Induction and statistical inference: probabilities associated with the mean and S. D. in samples, Fisher's notions of sufficiency, efficiency and consistency. Tests for the significance of a single mean and S. D. History of Bayes' rule and inverse probability. Fiducial probability. Two or more samples. The Chi-test and the analysis of variance. Least squares, or the minimizing of Chi-square. The significance of parameters estimated by least squares. Systematic computation.

Course D.—Electrochemistry—Dr. Edgar R. Smith. Sixty lectures given two hours per week throughout the year.

Outline of course: The topics covered in this course will include electrode reactions; electrolytic conductance and transference; thermodynamics of electrochemistry; Debye-Hückel theory of activity coefficients; the e.m.f. of cells as a means of determining equilibrium constants and changes in free energy, entropy and heat content of chemical reactions; and incidental topics such as Brönsted's theory of acids and

bases, electric moments of molecules in solution, standard cells, potentiometric titrations, etc. Prerequisites: Elementary calculus and physical chemistry.

The Educational Committee will welcome suggestions of other courses which might be arranged provided the registration is sufficient and suitable instructors may be obtained.

Tuition.—The fee for each sixty-lecture course will be fifteen dollars. If desired the tuition may be paid in two installments, $9.00 per course being due on or before November 1, 1935 and $6.00 on or before March 1, 1936.

For further information address the Educational Committee, National Bureau of Standards, Washington, D. C.

THE FRANKLIN INSTITUTE

STATED MONTHLY MEETING, OCTOBER 16, 1935.

The regular monthly meeting of The Franklin Institute was called to order at 8:15 o'clock by the President, Mr. Nathan Hayward, who immediately called upon the Assistant Secretary for the business of the evening. He reported that the proceedings of the last regular meeting of the Institute, the Medal Day Meeting, had been printed in the JOURNAL of the Institute for June, and that a detailed account of the Medal Day ceremonies was published in the August issue of the JOURNAL. He stated that if there were no objections or corrections, these minutes should now be approved. No objections were heard and the President therefore declared that the minutes were approved.

The Assistant Secretary then announced that the additions to membership since the last report were as follows: Resident Members—15; Non-Resident Members—7; Student Members—29; Museum: Family Memberships—2; Individual Memberships—5; Student Memberships—117, a total of 175.

There being no further business, the President introduced Dr. Harold C. Urey, Department of Chemistry, Columbia University, New York City, who addressed the meeting on "Heavy Water."

The speaker introduced his subject by describing the isotopes, the elements which consist of mixtures of atoms with very nearly identical chemical properties but differing atomic weights. They were discovered as a result of the study of radioactive substances, such as radium. The work of Sir J. J. Thomson, Dr. F. W. Aston and others was also reviewed. Rarer isotopes, namely those of carbon, nitrogen and oxygen, were discovered by a study of molecular spectra and the hydrogen isotope the so-called deuterium by the atomic spectra of these two varieties of hydrogen.

Water consists of a mixture of nine varieties of water. Since water is composed of one atom of oxygen and two atoms of hydrogen per molecule, it is possible to have water with any one of the three varieties of oxygen, namely, those of atomic weights 16, 17 and 18, combined with any one of three varieties of hydrogen having atomic weights 1, 2 and 3. The lightest of these waters would be that consisting of hydrogen of atomic weight 1, combined with oxygen of atomic weight 16. All other varieties of water might be referred to as heavy water.

The further fractionation of oxygen is the problem which has been attempted in several ways. The electrolytic method has been attempted but without appreciable success. The fractional distillation of water was used by G. N. Lewis to show that the varieties of oxygen might be separated in this way. No successful separation has been secured by this method up to the present, but it does appear to be a very interesting method to be used for this purpose.

The uses of separated isotopes can be illustrated in many ways. The chemical properties of hydrogen and deuterium are very distinctly different and

some examples of the results which have been published in the last few years were cited. A demonstration of the difference in melting points of these two varieties of water was shown.

The biological effects of these varieties of water are of very great scientific interest though it is doubtful if they will ever be used as medicines for the cure of disease. Their interest lies in their use to trace the course of chemical compounds through living organisms. Some illustrations of this effect have been published and were presented.

A discussion followed the paper in which Drs. Swann, Picard, Porter and others took part.

The President conveyed the thanks of those present to the speaker, and the meeting adjourned at 9:50 P.M.

ALFRED RIGLING,
Assistant Secretary.

COMMITTEE ON SCIENCE AND THE ARTS.

(*Abstract of Proceedings of Stated Meeting held Wednesday, October 9, 1935.*)

HALL OF THE COMMITTEE,
PHILADELPHIA, OCTOBER 9, 1935.

MR. CHARLES H. MASLAND, 2ND *in the Chair.*

The following report was presented for final action:

No. 2976: High Voltage Generator.

This report recommended the award of the Elliott Cresson Medal to Dr. Robert J. Van de Graaff, of the Massachusetts Institute of Technology, "In consideration of his development of an electrostatic generator for the production of high voltage direct currents, through which he has made possible the extension of nuclear investigation."

GEO. A. HOADLEY,
Secretary to Committee.

MEMBERSHIP NOTES.

ELECTIONS TO MEMBERSHIP.

RESIDENT.

MR. CRANDELL Z. ROSECRANS, Mechanical Engineer, Leeds and Northrup Company, Philadelphia, Pa. For mailing: 416 East Phil-Ellena Street, Philadelphia, Pa.

NON-RESIDENT.

MR. HARTMAN B. CANON, Electrical Engineer, Wells-Gardner and Company, Chicago, Illinois. For mailing: 4304 Drummond Place, Chicago, Illinois.

STUDENT.

MR. G. HOWARD BOYD, 418 South Forty-third Street, Philadelphia, Pa.
MR. GEORGE H. DAY, 223 West Gorgas Lane, Philadelphia, Pa.

Miss HELEN E. FOELL, Young Woman's Christian Association, 1800 Arch Street, Philadelphia, Pa.
Mr. MYER GRODSKY, 1939 West Somerset Street, Philadelphia, Pa.
Mr. ABRAHAM SHUCHMAN, 4188 Viola Street, Philadelphia, Pa.
Mr. LEON N. WEINER, 1139 North Forty-first Street, Philadelphia, Pa.

MUSEUM MEMBERSHIP.

FAMILY.

Mr. WALTER H. HARTUNG, 116 East Stratford Avenue, Lansdowne, Pa.
Mrs. CHARLES N. THORPE, 232 Church Road, Ardmore, Pa.

INDIVIDUAL.

Mr. GEORGE H. DUNKLE, Girard College, Philadelphia, Pa.
Dr. CLARENCE HODGES, Temple University, Philadelphia, Pa.

STUDENT.

Miss RUTH ALBERTSON, Philadelphia, Pa.
Miss EVA ALINCEWICZ, Philadelphia, Pa.
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Miss NAOMI ANTHONY, Philadelphia, Pa.
Mr. HAROLD ASH, Philadelphia, Pa.
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Mr. SIDNEY BROWN, Philadelphia, Pa.

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MISS MARION D. HOGELAND, Philadelphia, Pa.
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Mr. F. L. Morse, Ithaca, New York.
Mr. Ralph G. Putnam, Philadelphia, Pa.
Mr. A. F. Shattuck, Beverly Hills, California.
Mr. Sidney F. Tyler, Philadelphia, Pa.

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BOOK REVIEWS.

EXPERIMENTAL PHYSICS, by Edwin Morrison, M.S., and S. Elizabeth Morrison, B.S. 235 pages, illustrations, 21.5 × 28 cms. Philadelphia, P. Blakiston's Son & Co., Inc. Price $2.00.

The authors, both of Michigan State College, have presented here the method of procedure for sixty-five experiments suited for college work. Almost all of these experimental problems are considered as studies, with the aim of development of interest. In stressing this point the authors state, "Comparatively few college students fail in physics or college subjects in general, from lack of ability or capacity. But scores of them fail from lack of interest in college subjects."

The book opens with a brief introduction discussing common misconceptions of experimental physics and then gives a justifiable reason for experimental courses. Following this there are laboratory instructions, in general and with regard to laboratory reports and calculations and final results. The experiments themselves cover everything properly classified under the subject. Emphasis is placed upon manipulation, correct gathering and organization of data, solution by means of equations. In addition, analysis of observations and data, also the reasoning out of certain fundamental principles and conclusions are sought.

The book should adequately fulfill its purpose. As a matter of fact, one can hardly look through the volume without becoming interested in several of the topics treated.

R. H. OPPERMANN.

INVENTING THE SHIP, A STUDY OF THE INVENTIONS MADE IN HER HISTORY BETWEEN FLOATING LOG AND ROTORSHIP, by S. C. Gilfillan, Ph.D. 294 pages, illustrations, 14.5 × 20.5 cms. Chicago, Follett Publishing Company, 1935. Price $2.50.

The author gives in this book an historic account of the development of the merchant ship from the earliest times to the present. All the important ideas

conceived and added as regards main features, rigging, propulsive means, stearing gear, and general design and construction of the hull are given place. The purpose of the book however, is not to give this account for interesting reading alone, but to present the information from the viewpoint of invention, its social causes and effects. From this viewpoint most any subject can be chosen. The ship however is among the best for illustration.

The book is a companion volume to the author's "Sociology of Invention" which has been reviewed in these columns recently. There are six chapters devoted to the historic account proper. They cover the evolution of the sail ship, earlier steamship inventions, screw propulsion, up to the rotor ship and novelties. With regard to the rotor ship, the author gives quite a clear description how, by associating the Magnus effect and sails, it operates. The invention is startling, revolutionary and practical.

The last chapter is devoted to a history of ship designers and inventors. Much factual and interesting information is here revealed. The style of writing in this chapter is exceptionally noteworthy for the matter is presented in a summarization in periods of time which is most impressive to the average reader.

Throughout the book a great many citations are made of references. These citational notes are listed in Appendix I. A short bibliography on primitive invention, a select bibliography of histories of the ship and an index concludes the book.

The book can be easily understood by the average reader; all technical details being explained in the language of the non-technical. In this the author is to be commended. It attains its object admirably and besides being interesting reading, it should prove very useful as a reference work.

R. H. OPPERMANN.

CHEMICAL ANALYSIS OF ALUMINUM. Methods Standardized and Developed by the Chemists of the Aluminum Company of America, under the direction of H. V. Churchill and R. W. Bridges. 83 pages, 13 × 21 cms. New Kensington, Aluminum Research Laboratories, 1935. Price fifty cents.

What is ostensibly a treatise on the chemical analysis of aluminum is in reality a very up-to-date work on the quantitative determination of all the elements that might be connected with aluminum in any way. The number is surprisingly large and the result is a book of such broad scope that it represents an economical and valuable acquisition to all chemical libraries, even to those laboratories whose books are accommodated by a single shelf.

The analytical procedures have been tested thoroughly and in all probability are the most satisfactory so far known from the standpoint of convenience and accuracy. Besides aluminum, directions for the determination of thirty-six other elements are included. Some of these are classed as incidental impurities, some are valuable alloying constituents, others may have a damaging effect. To mention a few of the rarer members, they are beryllium, cerium, gallium, indium, lithium, molybdenum, tantalum, tellurium, vanadium and zirconium.

T. K. CLEVELAND.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

Report No. 518, The Drag of Airplane Wheels, Wheel Fairings, and Landing Gears. II—Nonretractable and Partly Retractable Landing Gears, by David Biermann and William H. Herrnstein, Jr. 10 pages, illustrations, 23 × 29 cms. Washington, Superintendent of Documents, 1935. Price ten cents.

This is the second paper giving the results obtained in the N. A. C. A. 20-foot wind tunnel on the drag due to landing gears. The first paper presented the results of tests made with full-scale models of wheels, wheel fairings, and landing gears intended for airplanes of approximately 3,000 pounds weight. The present report gives the results of tests of nonretractable and partly retractable landing gears intended for heavier low-wing monoplanes of the transport and bomber type.

The tests were made on 1/2.8-scale models of gears with a capacity of 16,000 pounds total weight. The landing gears were mounted on a wing of 5-foot chord, 15-foot span, and thickness of 20 per cent. of the chord. The effect of a radial-engine nacelle mounted in the leading edge of the wing on the drag of the landing gears was also investigated. Propeller tests were made in conjunction with several types of landing gears in order to ascertain the effect of the landing gears on the propeller characteristics.

The tests indicated that, in general, the presence of the engine nacelle did not appreciably affect the drag due to the landing gears. The retractable landing gears were at least one-half retracted into the wing or fairing before the drag became less than that due to the best nonretractable landing gears. Landing gears that were partly retracted into a nacelle near the maximum section or into the wing near the leading edge had a much higher drag than landing gears that were partly retracted farther aft on the wing. The drag due to streamline wheels used on partly retracted landing gears was less than that for low-pressure wheels. Landing gears that were partly or fully retracted into streamline fairings below the wing had only slightly greater drag than those that were partly retracted into the wing or nacelle. The propulsive efficiency was reduced from 1 to 3 per cent. by the presence of landing gears tested in conjunction with the propeller.

Report No. 520, A Comparison of Fuel Sprays from Several Types of Injection Nozzles, by Dana W. Lee. 38 pages, plates, 23 × 29 cms. Washington, Superintendent of Documents, 1935. Price twenty-five cents.

A series of tests was made of the sprays from 14 fuel-injection nozzles of 9 different types, the sprays being injected into air at atmospheric density and at 6 and 14 times atmospheric density. High-speed spark photographs of the sprays from each nozzle at each air density were taken at the rate of 2,000 per second, and from them were obtained the dimensions of the sprays and the rates of spray-tip penetration. The sprays were also injected against Plasticine targets placed at different distances from the nozzles, and the impressions made in the Plasticine were used as an indication of the distribution of the fuel within the spray. Cross-sectional sketches of the different types of sprays are given showing the relative sizes of the spray cores and envelopes. The characteristics of the sprays are compared and discussed with respect to their application to various types of engines.

Report No. 533, Distribution and Regularity of Injection from a Multicylinder Fuel-Injection Pump, by A. M. Rothrock and E. T. Marsh. 12 pages, diagrams, 23 × 29 cms. Washington, Superintendent of Documents, 1935. Price ten cents.

A six-cylinder commercial fuel-injection pump was adjusted to give uniform fuel distribution among the cylinders at a throttle setting of 0.00038 pound per injection and a pump speed of 750 revolutions per minute. The throttle setting and pump speed were then varied through the operating range to determine the uniformity of distribution and regularity of injection.

The variation in distribution among the cylinders reached a maximum of ± 17 per cent. at low pump speeds and one-tenth throttle setting. Above one-half throttle the variation was not more than ± 3.0 per cent. No effect on the distribution was produced by a change in the type of injection valve or injection-valve spring. As the valve-opening pressure or the residual pressure in the injection tube was reduced to a very low value the regularity of injections increased. The distribution was little affected. A stiffer injection-valve spring also produced more regular injections. Poor seating of the injection-valve stem caused a variation in the residual pressure in the injection tube.

Report No. 535, Hydrogen as an Auxiliary Fuel in Compression-Ignition Engines, by Harold C. Gerrish and Hampton H. Foster, 16 pages, illustrations, 23 × 29 cms. Washington, Superintendent of Documents, 1935. Price ten cents.

An investigation was made to determine whether a sufficient amount of hydrogen could be efficiently burned in a compression-ignition engine to compensate for the increase of lift of an airship due to the consumption of the fuel oil. The performance of a single-cylinder four-stroke-cycle compression-ignition engine operating on fuel oil alone was compared with its performance when various quantities of hydrogen were inducted with the inlet air. Engine-performance data, indicator cards, and exhaust-gas samples were obtained for each change in engine-operating condition.

Hydrogen could be burned satisfactorily at all loads up to and including cruising at compression ratios of 13.4 and 15.6 in sufficient quantities to compensate for the increase in lift due to the consumption of the fuel oil. In the cruising range the mixtures of fuel oil and hydrogen burned as efficiently as the fuel oil alone. At small power outputs, the mixture of fuel oil and hydrogen burned less efficiently than the fuel oil alone; whereas, for power outputs greater than that required for cruising, the mixtures of fuel oil and hydrogen burned more efficiently than the fuel oil alone.

For all loads except idling there was present in the exhaust water vapor weighing more than the fuel oil burned, approximately 25 per cent. more for all loads above cruising. When burning the maximum usable amount of hydrogen along with the fuel oil, the weight of water vapor was 80 per cent. more at full load and 200 per cent. more at small loads.

The engine always stopped firing when the fuel oil was cut off. Throughout the limits of the test conditions, it was never possible to auto-ignite the various mixtures of hydrogen and air but the injection of even a minute quantity of fuel oil

would cause the mixtures to burn. The engine showed no ill effects from the use of hydrogen and no change in engine operation was apparent.

Report No. 538, Altitude-Pressure Tables Based on the United States Standard Atmosphere, by W. G. Brombacher. 14 pages, tables, 23 × 29 cms. Washington, Superintendent of Documents, 1935. Price five cents.

The altitude-pressure tables of the United States standard atmosphere given in Technical Report No. 246 are reprinted since that report is out of print. Advantage is taken to make certain revisions in the text and particularly to extend the altitude range of the tables from 50,000 to 80,000 feet. These tables include: (I) Altitude in feet at pressure intervals of 0.1 millimeter of mercury in the range 20 to 200 millimeters of mercury and at intervals of 0.2 millimeter of mercury in the range 200 to 790 millimeters of mercury; (II) altitudes in feet at pressure intervals of 0.01 inch of mercury in the range 0.8 inch to 31.09 inches of mercury; and (III) pressures in both millimeters and inches of mercury and air temperatures for every 500-foot interval in the altitude range—1,000 to 50,000 feet and for every 1,000-foot interval up to 80,000 feet. The mean temperature of the air column is given for each of the altitudes in table III up to 50,000 feet.

The work was carried out at the National Bureau of Standards, in part with the coöperation and financial assistance of the National Advisory Committee for Aeronautics.

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A Symposium on Illumination, edited by C. J. W. Grieveson, 229 pages, illustrations, plates, 14.5 × 22 cms. Pittsburgh, Instruments Publishing Co. 1935. Price $4.50.

Principles of Metallography, by Robert S. Williams and Victor O. Homerberg. 313 pages, illustrations, 14 × 21 cms. New York and London, McGraw-Hill Book Company, Inc., 1935. Price $3.50.

Industrial Electronics, by F. H. Gulliksen and E. H. Vedder, 245 pages, illustrations, 15.5 × 23.5 cms. New York, John Wiley & Sons, Inc., 1935. Price $3.50.

The Metallography and Heat Treatment of Iron and Steel, by Albert Sauveur. 531 pages, illustrations, tables, 18.5 × 27.5 cms. Cambridge, University Press, 1935. Price $8.00.

Chemical Engineering Catalog, 1935, Twentieth Annual Edition. The Process Industries' Catalog of Collected, Condensed and Standardized Data on Equipment, Machinery, Laboratory Supplies, Heavy and Fine Chemicals and Raw Materials. 863 pages, 21 × 28.5 cms. New York, Reinhold Publishing Corporation, 1935.

U. S. Coast and Geodetic Survey, Special Publication No. 192. First and Second Order Triangulation and Traverse in North Carolina (1927 Datum), by Oscar S. Adams, 410 pages, tables, 15 × 23 cms. Washington, Government Printing Office, 1935. Price fifty cents.

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National Advisory Committee for Aeronautics, Technical Notes, No. 540, A Deflection Formula for Single-Span Beams of Constant Section Subjected to Combined Axial and Transverse Loads, by Walter F. Burke, 24 pages, tables, figures. No. 541, The Effect of the Angle of Afterbody Keel on the Water Performance of a Flying-Boat Hull Model, by John M. Allison, 10 pages, figures. No. 542, The Initial Torsional Stiffness of Shells with Interior Webs, by Paul Kuhn, 15 pages, figures. 3 pamphlets, 20 × 26 cms. Washington, Committee, 1935.

CURRENT TOPICS.

Lateral Steel Reinforcement Strengthens Brick Columns.—(*Iron Age*, Vol. 136, No. 7.) A series of tests recently conducted in the department of mechanics of the University of Wisconsin determined the properties of reinforced brick masonry columns. The tests showed that the effective strength of a reinforced brick masonry column equals the sum of three components: the strength of the plain masonry, the strength of the longitudinal steel at its yielding point and the lateral restraint given by steel hoops placed in the horizontal joints of a brick column. Lateral hoops in every joint served to increase the toughness and to some extent the strengths of the columns. The yield point of the ⅜ in. steel rounds used in the hoops was 53,800 lb. per sq. in. The strength of the fillett and spot welds in the 10 in. hoops after heating to 900 deg. C. (1652 deg. F.) and straightening while hot averaged 58,900 lb. per sq. in. of bar cross-section. Spot welds alone did not prove satisfactory.

R. H. O.

New Heat Resisting Alloy.—A new development of the A. O. Smith Corporation is announced in *Steel* for September 2. It is a heat resisting alloy of chromium-iron-aluminum type, known as Smith No. 10. It is now being used in heat treating furnaces for industrial and laboratory use, making available electric heat with metallic resistors for operation to 2400 deg. F. The new alloy may be rolled into wire from which it is possible to wind coils or make reverse bands and other shapes of heating elements. It may also be cast into resistors or furnace parts of any desired form. Accurate life tests indicate commercial life at 2300 to 2400 deg. F. Electrical resistance is about 1000 ohms per circular mil foot. After passing through a maximum at about 1700 deg. F. its resistance falls gradually and at 2300 deg. F. it is about 10 per cent. and at about 2600 deg. F. it is about 7 per cent. above the resistance at room temperature. These temperatures are black body temperatures of the wire in air. By determining the temperature to which sample must be heated to start fusion it was found the new alloy begins to melt at 2830 deg. F. Its density is 6.9 grams per cubic centimeter. The formation of a protective alumina film on the new alloy makes it highly resistant to the penetration of oxygen and it is due largely to this that the new alloy owes its excellent performance at high

operating temperatures. It can be welded to itself or to other leads of the nickle-chromium alloy by using wire as a filler rod.

R. H. O.

Plant to Make Rubber at 100 Degrees Below.—(*Refrigerating Engineer*, Vol. 30, No. 3.) Down to −100° F. will go the temperatures in one section of a new plant for manufacturing artificial rubber, it was announced by the duPont company in Wilmington early in August. Several years laboratory experiments have proved the commercial feasibility of this cold, the most intense to be used on a large scale in industry. It is a part of a scientific trend toward lower and lower temperatures, where important chemical changes can be made more readily than with heat which has so long been the chief source of man's mechanical domination over natural forces. The 100° cold will be used to separate from acetylene the substance mono vinyl acetylene, which is the base of synthetic rubber.

R. H. O.

The Passamaquoddy Tidal-Power Project.—(*Mechanical Engineering*, Vol. 57, No. 9.) Capt. HUGH J. CASEY furnishes a brief statement on the largest utilization of power from the tides the world has seen. Located in the vicinity of Eastport, Maine, the project will provide for the generation of power by creating and maintaining a low level pool about 37 sq. miles in area in Cobscook Bay, by the construction of a series of dams, a power house, and an emptying-gate structure between Cobscook Bay and the Bay of Fundy. It is planned that the interior basin shall be maintained at or near low tide levels. As the tide rises and the difference in head between the sea and the basin exceeds 5 ft. the power house will be opened and power generated from the rising tide. The mean range of tide at this locality is approx. 18 ft. Power is likewise generated during falling tide. In the absence of an auxiliary means of generation of power, this arrangement would provide no primary power, due to the necessity of shutting down the power house during lower tide levels for 5 hr. intervals twice a day. Provision is made for a pumped storage plant near Haycock Harbor, 15 miles distant. Surplus peak power generated at the main tidal power plant at and near high tide is transmitted to a large pumping plant located on the sea near Haycock which pumps water into a large reservoir 125 to 135 ft. above sea level. During the shut-down periods of the main tidal power plant, this stored water is used to generate power at the Haycock power plant. The initial development will be adaptable to a much larger two basin development utilizing both Passamaquoddy and Cobscook Bays.

R. H. O.

Gas Cultivated Tomatoes.—(*Gas World*, Vol. CIII, No. 2663.) In a glass house 100 ft. by 30 ft. at Peakhurst, near Sydney, MR. C. DEVINE is pioneering a new development in the tomato-growing industry, at least in Australia. Using varieties of tomatoes from the Channel Islands, New Zealand and the United States, he expects, with the aid of a gas heating installation to garner 10 lb. of fruit from each of 1,000 plants at the end of October, just when it will be almost impossible to secure a tomato in Sydney. The heating plant installed consists of two units, thermostatically controlled at opposite ends of the house. The soil is heavily fertilized with 18 loads of manure, half a bag of superphosphate and a half a bag of bone dust. This is the first adaption of gas for heating in this way in the southern hemisphere.

R. H. O.

Electric Anemometer For Air Conditioning.—(*Elec. World*, Vol. 105, No. 18.) To measure air stream velocities W. V. HUKILL of the Bureau of Agricultural Engineering has devised a simple apparatus probably useful for air currents in any direction. It consists of a thermocouple, both junctions of which are exposed to the air stream. One junction is heated by current from two dry cells. The e.m.f. of the couple is a measure of the temperature difference and the faster the rate of air movement the less the temperature difference. Current value is measured by potentiometer and adjusted to the desired value by rheostat. The resulting thermocouple e.m.f. is converted directly to air velocities in feet per minute. The instrument has been used successfully in studying horizontal air movement in refrigerator cars where velocities range from 10 to 100 ft. per minute.

R. H. O.

A New Method of Water Heating.—(*American Gas Journal*, Vol. 143, No. 3.) In an attempt to reach the market for a domestic gas water heater of low first cost and a minimum operating cost the Handley Brown Co. of Jackson, Mich. has developed a new heater that transfers the heat to the water by reflection. Its trade name is Mirro-Shell. The utilization of this principle in proper design makes in a few minutes an efficient automatic storage gas water heater out of a range boiler regardless of the type of fuel previously used to heat the water. Highly polished, non-tarnishable metal mirrors are placed around the range boiler so as to reflect through its sides the heat generated by a small gas flame at the base of the tank. A surprisingly high over-all operating efficiency is obtained.

Costly and bothersome lining sediment and condensation troubles are eliminated.

R. H. O.

Eutectic Ice.—(*Power Plant Engineering*, Vol. XXXIX, No. 9.) Salt ice or frozen sodium chloride brine is now being introduced for use in refrigerated delivery trucks, store cabinets, railroad L. C. L. containers and in various other places where Dry Ice, mixtures of ice and rock salt, or mechanical refrigeration have been generally utilized. It is available in two forms: small, loose, broken ribbons, and compressed blocks, weighing approximately 30 lb. each. The refrigerant is made from brine composed of approximately 23 per cent. salt and 77 per cent. water by weight, the proportions having the lowest possible melting point (− 6° F.) for salt and water mixtures. The frozen brine melts at a temperature lower and more uniform than can be obtained with mixtures of salt and crushed ice, and its heat-absorbing capacity is considerably greater. Advantages for its use include: small quantities are required, no mixing is necessary, and no sludge or precipitate remains after melting. Ice cream, commercial lots of frozen foods, fish, meat and vegetables have been successfully refrigerated with frozen brine.

R. H. O.

Compact Impulse Generator.—(*Elect. World*, Vol. 105, No. 18.) The Ohio Brass Company has developed a new surge generator capable of delivering 3,000,000 volts for the study of lightning and insulation problems. It consists of two sections—a 2,000,000 volt portable indoor impulse generator to which a 1,000,000 volt section can be added for outdoor tests on full-sized tower and equipment set-ups. Capacitator units of the generator are arranged in a helical path on a hexagonal framework of porcelain-pillar insulators of standard assembly, with terminal bushings turned inward. A rotating column of pillar insulators in the center of the generator assembly controls sphere gaps which act as high voltage switches connecting the capacitator banks in series at discharge. The mechanism for regulating the sphere gaps permits the operator to vary the impulse voltage delivered by the generator without the necessity of shutting down the unit to make the adjustment manually. A synchronous clock control motor relieves the operator from continually throwing switches while the set is in operation and times the charge of the generator accurately, so that the same voltage may be obtained on successive discharges.

R. H. O.

Butane as Fuel and Refrigerant.—ARLAN E. DEBURN in *Western Gas* for September 1935 relates how a fuel consisting of approximately 25 per cent. propane, 50 per cent. iso-butane and 25 per cent. *n*-butane provides free refrigeration from the latent heat of vaporization, augmented by reliquefaction when there is not sufficient fuel consumption to maintain desired temperatures at June Lodge, a mountain resort at June Lake, Mono County, Calif. The fuel is used for auxiliary heat from butane-fired hot air furnaces on chill evenings and for heating cottages and bath houses surrounding the main lodge. Fuel usage for this purpose makes refrigeration feasible. The butane is blended in the Los Angeles basin and transported to the Lodge elevation of 7,600 ft. and 358 miles distant by motor truck in 3,000 gallon shipments. From the tanker the fuel is pumped into the 4,000 net gallon storage tank and stored under 60–80 lb. pressure.

R. H. O.

THE FRANKLIN INSTITUTE

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Wonderland of Science NOTES

NOVEMBER, 1935

FALL AND WINTER SCHEDULE OF HOURS.

Wed.	2 p.m. to 10 p.m.
Thurs.	2 p.m. to 10 p.m.
Fri.	2 p.m. to 10 p.m.
Sat.	10 a.m. to 10 p.m.
Sun.	2 p.m. to 10 p.m.

(Holidays same as Saturdays.) Closed Christmas Day.

PLANETARIUM DEMONSTRATIONS

(Lasting about 45 minutes.)

Wed.	3 p.m.		8:30 p.m.
Thurs.	3 p.m.		8:30 p.m.
Fri.	3 p.m.		8:30 p.m.
Sat. 12 m.	3 p.m.	4 p.m.	8:30 p.m.
Sun. and Holidays	3 p.m.	4 p.m.	8:30 p.m.

RADIO BROADCASTS.

The following radio broadcasts in dialogue form will be given (through the courtesy of Station WCAU) on each Saturday evening, at 6:00 o'clock during November. These broadcasts are given from the Lecture Hall of the Institute and are free to visitors to the Institute.

Nov. 2d, Major Victor Dallin (Officer commanding the 103rd Observation Squadron): "Wings and Ports."

Nov. 9th, G. S. Bliss, Esq. (Director, U. S. Weather Bureau): "Whether It's the Weather."

Nov. 16th, Dr. Ivor Griffith (College of Pharmacy and Science, Philadelphia): "The Chemical Revolution."

Nov. 23d, Dr. J. M. Pearson (The Sun Pipe Line Company): "Exploring Downwards."

Nov. 30th, Henry B. Allen, Esq., Director: Subject to be announced.

THE FRANKLIN INSTITUTE.
RECORD OF PLANETARIUM AND MUSEUM ATTENDANCE FROM NOVEMBER 6, 1933 TO OCTOBER 1, 1935.

	Free Admissions Members	Free Admissions Schools	Paid Admissions	Receipts	Total Attendance
Planetarium:					
From 11/6/33–10/1/34....	1,271	79,744	178,503	$ 44,611	259,518
* From 10/1/34–10/1/35....	3,126	60,549	116,087	28,519.95	179,762
Totals.....	4,397	140,293	294,590	$ 73,130.95	439,280
Museum:					
From 1/1/34–10/1/34.....	2,093	57,575	181,567	$ 45,362.45	241,235
* From 10/1/34–10/1/35....	7,440	63,104	207,988	50,792.95	278,532
Totals.....	9,533	120,679	389,555	$ 96,155.40	519,767
Recapitulation:					
From 11/6/33–10/1/34....	3,364	137,319	360,070	$ 89,973.45	500,753
* From 10/1/34–10/1/35....	10,566	123,653	324,075	79,312.90	458,294
Grand Totals.....	13,930	260,972	684,145	$169,286.35	959,047

* Fiscal Year.

THE FELS PLANETARIUM PROGRAM FOR 1935–36.

Demonstrations of the Planetarium, accompanied by explanatory talks, will be given as follows:

November, Stars and Nebulae; December, Architecture of the Universe; January, 1936, Evening Skies of Winter; February, Time and Navigation; March, The Calendar; April, How Will the World End? May, Eclipses; June, Stars at the North Pole.

Synopses of November and December Demonstrations.

November—"Stars and Nebulæ."

The vast cloud of glowing gas known as the Great Nebulæ in Orion, the nearest galaxy of stars outside our own Milky Way system, stars that change mysteriously in brilliance—these will be some of the featured performers in the Plane-

tarium demonstration during November. Visitors will be shown the evening skies at this time, and these objects pointed out. Brief explanations, telling why they are interesting, will be given, supplemented by views showing how they appear through the largest telescopes. The climax of the demonstration will be a reproduction of the great shower of shooting stars seen in November of 1833.

December—"The Architecture of the Universe."

In ancient times men believed that the stars were lamps hung on a vaulted ceiling not many miles above the ground. Now it is known that our Sun, and the stars we see in the night sky as well, are part of a great disc-shaped structure so vast that light takes about a hundred thousand years to cross, and that there are myriads of similar systems in the universe. The fascinating story of how these facts have been learned, will be told in popular language during the Planetarium demonstrations in December.

The Planetarium hall is air-conditioned and the chairs have been specially constructed to enable the visitor to view the sky without discomfort.

Admission to the planetarium 25 cents per person.

A SERIES OF SIXTEEN LECTURE-RECITALS TO BE GIVEN ON THE SECOND AND FOURTH SUNDAYS OF EACH MONTH ON THE ORIGIN AND HISTORY OF MUSIC FOR THE GENERAL PUBLIC BY GUY MARRINER, PIANIST AND COMPOSER.

Sunday, November 10th, 4 o'clock P.M. Medieval tone systems. Guido d'Arezzo. Musical notations. *Sonatas* by Kuhnau, Mozart, Beethoven and Brahms.

Sunday, November 24th, 4 o'clock P.M. Organum; discant; rondel; motet, duple time; faburden. Fifteenth century contrapuntal school. Carvalho. *Fugues* by Bach, Scarlatti, Mendelssohn and Brahms.

Admission: Ticket for the Series, $3.00.

WOMEN'S CLUB ACTIVITIES.

Widespread attention is directed to the conferences of Federated Women's Clubs, to be held in the Lecture Hall of The Franklin Institute.

To further the educational and scientific interest of women in the Museum of the Franklin Institute these meetings have been arranged by The Franklin Institute and the *Ladies' Home Journal*, through the courtesy of Mr. George Horace Lorimer.

The Programme

Philadelphia County Federation of Women's Clubs and Allied Organizations (Mrs. H. Childs Hodgens, *President*, presiding). OCTOBER 31ST.

1:45 P.M., meet in Lecture Hall.

1:55 P.M., Welcome by Mrs. Bruce Gould, Editor *Ladies' Home Journal.*

2:05 P.M., Speaker—Mrs. Louise Paine Benjamin, Beauty Editor *Ladies' Home Journal:* "Beauty and the Scientific Beast."

3:00 P.M., Planetarium Demonstration—"The Southern Cross."

3:40 P.M., Special Exhibit—Hall of Graphic Arts.

Delaware and Montgomery Counties Federation of Women's Clubs (Mrs. J. LeRoy Smith and Mrs. Allan M. Craig, *Presidents*, presiding). NOVEMBER 7TH.

1:45 P.M., meet in Lecture Hall.

1:55 P.M., Welcome by Mr. Henry Butler Allen, Director, Museum of The Franklin Institute.

2:05 P.M., Speaker—Miss Julia Coburn, Fashion Editor *Ladies' Home Journal:* "Where Do Fashions Come From?"

3:00 P.M., Planetarium Demonstration—"Stars and Nebulæ."

3:40 P.M., Special Exhibit—Hall of Aviation.

First District of New Jersey Federation of Women's Clubs (Mrs. William Chalmers Davis, *Vice-President*, presiding). NOVEMBER 21ST.

1:45 P.M., meet in Lecture Hall.

1:55 P.M., Welcome by Mrs. Lucretia Blankenburg.

2:05 P.M., Speaker—Miss Elizabeth Woodward, Sub-deb Page, *Ladies' Home Journal:* "A Girl Must Have a Private Life."

3:00 P.M., Planetarium Demonstration—"Stars and Nebulæ."

3:40 P.M., Special Exhibit—Hall of Electrical Communications.

A HINT FOR CHRISTMAS SHOPPING.

There is no need for a tiresome search for an appropriate and welcome gift! A Membership will give instructive entertainment throughout the year. The recipient will be notified of the gift on an attractive card mailed in time to be received on Christmas Eve.

Members are admitted free to the Wonderland of Science and the Planetarium, at all times, and they will receive notice of special demonstrations, such as those mentioned elsewhere. For students in school or college who are over twelve and under twenty-five years of age, the cost of membership is $2.00, for others $5.00, Family Membership, including all the members of a single household, costs $10.00 and a membership card is sent to each individual.

Checks should be drawn to the order of The Franklin Institute and mailed The Parkway at Twentieth Street, Philadelphia, together with a list of the names and addresses of the recipients.

It is felt that in spite of the low price of admission, the possession of a membership encourages frequent and less hurried visits to the Institute, which are apt to be less tiring and more instructive and entertaining than occasional longer visits.

SOME OF THE MORE RECENT EXHIBITS PLACED IN YOUR "WONDERLAND OF SCIENCE."

Have you seen—

The bones of your hand with the X-ray machine?

The beautiful models of ancient carriages which were donated by Mrs. J. L. G. Ferris?

The small working gasoline engine which carried a model plane in continuous flight for 22 minutes on $1\frac{3}{8}$ ozs. of gasoline?

Prints, etchings, wood-cuts and lithographs lent by Mr. R. Lessing Rosenwald?

The mural entitled "Sources of Color" painted and donated by Mr. F. W. Weber?

Four demonstrations of the principles of wind instruments donated by C. G. Conn Ltd.?

These as well as many more working exhibits are waiting for a visit from you.

THE ROMANCE OF DYES.

At the present time and running until about the last of November, a brief demonstration on the "Romance of Dyes" is presented daily in the Chemistry Section of the Franklin Institute.

This lecture, illustrated with many spectacular demonstrations, gives the public some idea how the brilliant dyes are made from coal. Beginning with a short historical sketch of the use of dyes and color, we see the extraction of the dyes, cochineal and logwood, from their natural sources. Following the distillation of coal to produce coal tar, we follow the chemist through the construction of Para Nitraniline Red and finally to the climax, a rainbow of color produced on a large scale, from the four dye building blocks of the chemist—carbon, hydrogen, oxygen and nitrogen.

Illustrating the use of dyes, three spectacular dyeing demonstrations are shown; first, direct dyeing; second, vat dyeing; and finally selective dyeing. These demonstrations are given Wednesdays to Fridays inclusive at 4 o'clock P.M., and Friday at 8 o'clock P.M., Saturday at 1.00, 2.30 and 4 o'clock P.M. and Sunday at 2.30 and 4.00 o'clock P.M.

Beginning in December we will show in the Chemistry Section, how the chemist takes these same four elements and instead of making a house of dyes, makes a house of perfumes.